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Univ. of Michigan). This is the first report on a clear observation of the magnetic phase transition temperature (above 300 K) in an arsenide-based heterostructure.

Symposium Support: NREL, NSF, Omicron NanoTechnology USA, and Veeco Instruments.

[redacted]ghting Drive Ga[redacted]

(See MRS Proceedings Volume 798)

[redacted]scussed in Sympo[redacted]related alloys were [redacted] lasers and LEDs, bulk substrates, heteroepitaxy, nanostructures, indium nitride, electronic devices, advances in processing, and various characterization techniques. The drive for UV sources and solid-state lighting continues to be an active area, with researchers reporting power levels reaching 20 mW at 280 nm under high injection conditions. There is still much room for improvement in terms of the efficiency of these devices. UV lasers were also reported with wavelengths in the range of 358–380 nm. Different approaches to achieving bulk GaN and AlN substrates were discussed. For bulk substrates, the main issue is still the limited size. However, in the short term, quasi-bulk substrates grown by HVPE and lifted off from the original substrates seem to be the best solution.

Heteroepitaxy of GaN on silicon is gaining a lot of attention, with the possibility of integration. In the nanostructures session, GaN QDs grown by both MOCVD and MBE were reported. In the area of impurity doping, there were presentations on Mg incorporation for *p*-type GaN, Mn doping for spintronics, and rare-earth doping for luminescent devices. Another interesting development is the convincing evidence that the direct bandgap of InN is ~0.65 eV, based on material with higher crystallinity. However, the issue of a high residual background electron concentration still needs to be addressed. Preliminary results on InN-based solar cells were also presented.

Symposium Support: AFOSR, ARO, DARPA, and ONR.

Understanding Brought to Behavior of Hydrogen in Compound Semiconductors

(See MRS Proceedings Volume 799)

Symposium Z brought together discussions of the materials properties and the consequences for electronic and optoelectronic device applications of a range of semiconductor materials including III–V alloys, ZnO, and quantum structures. C.G. Van de Walle (Palo Alto Research Center) tied many of these materials together with a unified theoretical treatment of the effects of hydrogen in com-

Graduate Students Receive Gold and Silver Awards

During an awards ceremony held on December 3 at the 2003 Materials Research Society Fall Meeting, graduate student finalists received Gold and Silver Awards.

***Gold Graduate Student Awards** went to (row 1, left to right): **Gary R. Maskaly** (Massachusetts Institute of Technology), **Olaf Gelhausen** (University of Technology, Australia), **David M. Pustai** (University of Delaware), **Gregory M. Gratson** (University of Illinois, Urbana-Champaign), and **Congjun Wang** (University of Chicago); (row 2, left to right): **Haimei Zheng** (University of Maryland), **Jessica Winter** (University of Texas, Austin), **Suniti Moudgil** (Massachusetts Institute of Technology), and **Ilke Arslan** (University of California, Davis); and (row 3, left to right): **Daniel B. Aubertine** (Stanford University), **Francesca Iacopi** (IMEC, Belgium), **Sarah M. Estrada** (University of California, Santa Barbara), **Amanda J. Haes** (Northwestern University), and **Egon Gross** (Technische Universität Munchen, Germany). Not shown is **Rongchao Jin** (Northwestern University).*

***Silver Graduate Student Awards** went to (row 1, left to right): **Manuel Garcia-Leiner** (University of Massachusetts, Amherst), **Ting Xu** (University of Massachusetts, Amherst), **Aditi S. Risbud** (University of California, Santa Barbara), **Miri Kazes** (Hebrew University, Israel), **Weidong Li** (University of Delaware); (row 2, left to right): **Joshua Goldberger** (University of California, Berkeley), **Junling Wang** (University of Maryland), **Shirley Ying Meng** (Singapore–Massachusetts Institute of Technology Alliance, Singapore), **Cynthia A. Mitchell** (University of Houston), **Maria M.F. Cortalezzi** (Rice University), and **Ho Won Jang** (Pohang University of Science & Technology, South Korea); and (row 3, left to right): **Olivier Guise** (University of Pittsburgh), **Aleksandar Spasic** (Boston College), **Thomas E. Vandervelde** (University of Virginia), **Brandon L. Seal** (Arizona State University), **Alexander B. Artyukhin** (University of California, Davis), and **Sungjee Kim** (Massachusetts Institute of Technology). Not shown are **Tommaso Baldacchini** (Boston College), **James Zachary Hilt** (University of Texas, Austin), and **Evgenia Kim** (Moscow State University, Russia).*

SYMPOSIUM Y

Y: GaN and Related Alloys

December 1 - 5, 2003

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* Invited paper

SESSION Y1: Optical Devices
Chair: Michael Wraback
Monday Morning, December 1, 2003
Room 312 (Hynes)

8:30 AM *Y1.1
Ultraviolet Laser Diodes With AlGaN and InAlGaN Multiple-Quantum-Well Active Regions.*. Michael Kneissl, Palo Alto Research Center Inc. (PARC), Palo Alto, California.

We will report on the design and performance characteristics of AlGaN and InAlGaN multiple-quantum-well (MQW) laser diodes emitting in the ultraviolet spectral region. The nitride laser diodes were grown on (0001) c-plane sapphire substrates by metal organic chemical vapor deposition. Under pulsed bias conditions, laser operation was obtained in gain-guided laser devices with uncoated mirror facets and cavity lengths ranging from 300 to 1500 μm. For laser diodes with AlGaN MQW active regions, room-temperature threshold current densities as low as 23 kA/cm2 have been achieved with emission wavelengths between 361.6 nm and 358.5 nm. This is the shortest emission wavelength yet reported for a semiconductor laser diode. The maximum output power for AlGaN MQW laser diodes was 45 mW per facet with differential quantum efficiencies of 1.3%. Slightly improved performance has been obtained for laser diodes with InAlGaN MQW active regions. The indium composition in the quantum wells ranged from 0.5% to 3% and the aluminum content varied between 2% and 4%. Pulsed laser operation has been obtained with threshold current densities between 13 and 18 kA/cm2, with emission wavelength ranging between 362.4 nm and 359.9 nm. Light output powers greater than 80mW under pulsed current-injection conditions and differential quantum efficiencies of 4.2% have been achieved. Finally, growth of UV laser diode heterostructures on low dislocation density substrates, like GaN or AlN, will be discussed.
*The work was partially supported by the Defense Advanced Research Projects Agency SUVOS program under SPAWAR Systems Center Contract No. N66001-02-C-8017. 1. Michael Kneissl, David Treat, Mark Teepe, Naoko Miyashita, Noble M. Johnson, Appl. Phys. Lett. 82, 2386 (2003). 2. Michael Kneissl, David Treat, Mark Teepe, Naoko Miyashita, Noble M. Johnson, Appl. Phys. Lett. 82, 4441 (2003).

9:00 AM Y1.2
208 nm Ultraviolet (UV) Light Emitting Diodes on Sapphire and Bulk AlN Substrates. Xuhong Hu[1], Qhalid Fareed[1], Remis Gaska[1] and Asif Khan[2]; [1]Sensor Electronic Technology, Inc., Columbia, South Carolina; [2]Department of EE, University of South Carolina, Columbia, South Carolina.

We report on epitaxial growth, fabrication, and characterization of 298 nm ultraviolet (UV) LEDs on sapphire and bulk AlN substrates. Single crystal bulk AlN substrates of approximately 4x5 mm size and 1 mm thick were supplied by Crystal IS, Inc. The LEDs structures were grown on the Al face slightly off-axis double side polished substrates. The devices were mesa etched. The power levels of about 350 uw at 70 mA have been achieved for devices with the cross sections of 200x200 um for LEDs on sapphire substrates. We also demonstrated, for the first time, the UV emission at 298 nm for LEDs on bulk AlN substrates. For this first demonstration, we used the same design that was optimized for sapphire substrates. This resulted in smaller power levels for the LEDs on bulk AlN, since the strain distribution that plays the key role in the UV design is completely different for devices on bulk AlN. The design optimization for these devices will be discussed.

9:15 AM Y1.3
High Current Injection to a UV-LED grown on a Bulk AlN Substrate. Toshio Nishida[1], Tomoyuki Ban[2], Hisao Saito[3] and Toshiki Makimoto[1]; [1]Physical Science Laboratory, NTT Basic Research Laboratories, NTT Corporation, Atsugi, Kanagawa, Japan; [2]NTT Electronics, Atsugi, Kanagawa, Japan; [3]NTT TechnoSupport, Atsugi, Kanagawa, Japan.

We fabricated an AlGaN-based ultraviolet light emitting diode (UV-LED) on a bulk AlN substrate. The device shows improved saturation characteristics in its output power under high current operation. Thermal conductivity and transparency of the substrate material are important for high flux extraction from LEDs. Heat dissipation improves the radiative carrier recombination and reduction of the UV light absorption enhances the extraction efficiency. Bulk AlN is UV transparent and has high thermal conductivity of 2.85 W/cm K, which is much higher than that of the conventional sapphire substrate (0.23 W/cm K) usually used for nitride devices. It also has the benefit of the same crystallographic symmetry as that of AlGaN which consists short wavelength UV-LEDs. We grew an undoped AlGaN buffer layer and a Si-doped AlGaN current supply layer after growing an AlN layer homoepitaxially on a bulk AlN substrate. The device consists of an AlGaN single quantum well (AlGaN-SQW) sandwiched by p-type and n-type carrier blocking layers [1] and short-period-alloy superlattice (SPASL) cladding layers[2]. The emission wavelength was 345 nm. For comparison, we fabricated a reference device on a high quality AlN template layer grown on a sapphire substrate[3]. The p-type electrode areas are 300 x 300 micrometers square, and output powers are measured under bare-wafer geometry on a metal block. The output power of the UV-LED on the bulk AlN substrate increased almost linearly up to 300 mA and saturated at the injection current of 400 mA, which is two times higher than that of the reference device. [1]T. Nishida, et al., Appl. Phys. Lett., 78 (2001) p.399, [2]T. Nishida, et al., IPAP Conf. Ser. 1 (2000) p.872, [3]T. Nishida et al., Appl. Phys. Lett., 82 (2003) p.1.

9:30 AM Y1.4
GaN Quantum Dot UV Light-Emitting Diode. Jeong-Sik Lee[1], Satoru Tanaka[2], Peter Ramvall[1] and Hiroaki Okagawa[3]; [1]R & D center, Nippon EMC LTD, Tama-shi, Tokyo, Japan; [2]Research Institute for Electronic Science, Hokkaido University, Sapporo, Hokkaido, Japan; [3]Photonics Laboratory, Mitsubishi cable industries, Itami, Hyogo, Japan.

Optical devices operating in the UV region are increasingly important due to possible future applications in white light-emitting diodes (LEDs), high density versatile disks, medical and environmental tools, etc. White LEDs are especially interesting to replace conventional fluorescence lamps due to advantages such as lifetime, reliability, and environmental issues. Several attempts have been made to manufacture UV LEDs mainly by lowering the In content in InGaN quantum wells (QWs). However, by this approach the external quantum efficiency drastically decreases with reduced In fraction. The reason for this might be a lack of localized states in the InGaN QWs. A possible way to overcome this problem is to introduce such states artificially; i.e. to add quantum dots (QDs) in the active layer. Tanaka et al. [1] reported GaN QD formation using Si as antisurfactant, which made it possible to grow GaN QD structures on AlxGa1-xN (x~0.1) surfaces. With this approach, we recently succeeded in fabricating a GaN QD LED by metal-organic vapor phase epitaxy (MOVPE). [2]. In this work we discuss the details of a QD LED structure consisting of p- and n-type AlxGa1-xN (x~0.1) layers and GaN QDs ~4.5nm high and ~20nm in diameter with an approximate density of 5x1010cm-2 as measured by AFM. Electroluminescence (EL) measurements at room temperature with several different injection currents were performed. Two peaks at 3.44eV and ~3.58eV, which originates from the GaN QDs and the AlxGa1-xN cap layer, respectively, are visible. The origin of the EL is explained by comparing it to photoluminescence (PL) measurements. We also compare the quantum efficiency of LEDs containing QDs with similar structures without QDs. [1] S. Tanaka, S. Iwai, and Y. Aoyagi: Appl. Phys. Lett. 69, 4096 (1996) [2] S. Tanaka, J.-S. Lee, P. Ramvall, and H. Okagawa, Jpn. J. Appl. Phys. (2003)

9:45 AM Y1.5
Deep UV Light-Emitting Diodes Using AlGaN/AlGaN Heterostructures Grown by Metalorganic Chemical Vapor Deposition. Uttiya Chowdhury, Tinggang Zhu, Michael M. Wong, Dongwon Yoo and Russell D. Dupuis; Microelectronics Research, Univ. of Texas at Austin, Austin, Texas.

The AlGaN material system enjoys high scientific and technological interest because of its prospect for development of deep UV light emitting diodes (LEDs). We report on the material growth conditions, device fabrication and measurement of deep UV light emitting diodes using AlGaN/AlGaN heterostructures grown using Metalorganic Chemical Vapor Deposition (MOCVD). The epitaxial layers were grown on both-side polished c-plane sapphire substrates for development of back-side illuminating LEDs. A multiple low temperature buffer layer scheme was used to grow a thick AlGaN template layers without cracking. Reduction of threading dislocation density using this scheme was studied using transmission electron microscopy. The layers were grown in an Emcore D125 UTM rotating disk reactor using a growth pressure from 50 to 200 Torr and growth temperature from ~1050 to 1070C. Developed for mesa geometry devices, the resistance of the bottom n-contact layer plays a decisive role in the forward resistance of the devices. Due to the use of back-side illuminating structure, the layer also has to be transparent to the device luminescence ($\lambda \sim 280$ to 300 nm). We developed a 0.5 μm thick n-contact layer for this purpose having a sheet resistivity of ~1000 Ω/square as measured by contactless resistivity probe. Transparency to wavelength of interest was verified using optical transmittance measurement. LEDs were grown using both single quantum well (SQW) and 3 quantum well structures using of $Al_{0.42}Ga_{0.58}N$ quantum wells. Diode I-V characteristics show a differential forward resistance of 100-130 Ω. As-grown device structures display a strong room-temperature cathodoluminescence and photoluminescence response. The DC electroluminescence (EL) spectra under low current injection exhibited a sharp peak near the QW bandedge ($\lambda \sim 290$ nm) with a linewidth of 9 nm. We also

investigate the effects of a current-blocking layer to eliminate or reduce luminescence from the GaN cap layer.

10:30 AM *Y1.6
Light Emission Devices Using Polar and Non Polar III-N Films. M. Asif Khan, Department of Electrical Engineering, University of South Carolina, Columbia, South Carolina.

In this paper we will discuss the progress that we have made in fabricating high efficiency deep ultraviolet light emission devices (LEDs) over c-plane sapphire substrates. Results will be presented of a comparative study of devices with ternary AlGaN and quaternary AlInGaN multiple quantum well (MQW) active regions. With improved buffer layers and active region designs we can now achieve milliwatt powers for devices with peak emission from 275nm to 340 nm. These devices are well suited as pumps for phosphors for visible and white light generation. Recently, for the first time we have also succeeded in fabricating UV-visible LEDs using non-polar AlInGaN-InGaN MQWs over r-plane sapphire substrates. The buffer layers for these non-polar devices comprised of thick low defect GaN layers which were deposited using a unique selective area lateral epitaxy (SALE) procedure. The materials growth and device characterization results for the polar and the non-polar LEDs will be compared to discuss the role polarization plays in III-N devices.

11:00 AM Y1.7
Flip-chipped 280 - 300 nm UV LEDs with Interdigitated Contacts for Efficient Carrier Injection. Arthur J Fischer, A. A. Allerman, M. H. Crawford, K. H. A. Bogart, W. W. Chow, R. J. Kaplar, S. R. Kurtz, S. R. Lee, D. D. Koleske, K. W. Fullmer, J. J. Figiel and F. Jalali; Sandia National Labs, Albuquerque, New Mexico.

Although LEDs emitting below 300 nm are desired for fluorescence-based detection of biological agents, the demonstration of LEDs emitting in the deep UV presents significant materials and device challenges. For high Al AlGaN films, both n-type and p-type doping become increasingly more difficult as the Al concentration increases. This low doping efficiency combined with low mobilities and high sheet resistances, make it particularly difficult to efficiently inject carriers into deep UV LED active regions. In order to address these materials issues we have developed a flip chip LED process where interdigitated contacts are used to reduce lateral current spreading problems and improve overall device efficiency. These contacts have been applied to LED die with emitting areas as large as 1 mm^2. Deep UV LED wafers were grown by metalorganic chemical vapor deposition on sapphire substrates beginning with a low temperature AlN nucleation layer followed by a 47% AlGaN base layer. In one design, the LED active region consisted of three $Al_{0.15}Ga_{0.85}N$ quantum wells with $Al_{0.47}Ga_{0.53}N$ barriers which showed LED emission over a range from 290 to 300 nm. The LED was capped with a 500$\AA$ of p-type $Al_{0.47}Ga_{0.53}N$ followed by 500$\AA$ of p-type GaN for use as a contacting layer. Devices were flip chipped to Si or SiC submounts and UV photons were emitted through the transparent AlGaN base layer and sapphire substrate. LEDs showed continuous wave output powers as high as 140 μW at 130 A/cm^2 with voltages on the order of 12 volts at 20 mA. Recent device performance results for various AlGaN-based QW active regions will be presented. Critical performance issues for both small and large area die, including the competition between quantum well emission and deep level emission, current spreading, light extraction and thermal management, will be discussed. *Sandia is a multiprogram laboratory operated by Sandia Corporation, for the United States Department of Energy under Contract DE-AC04-94AL85000

11:15 AM Y1.8
High Power 330 nm AlInGaN UV LEDs in the High Injection Regime. Maria Gherasimova[1], J. Su[1], G. Cui[1], J. Han[1], H. Peng[2], E. Makarona[2], Y. He[2], Y.-K. Song[2] and A. V. Nurmikko[2]; [1]Electrical Engineering, Yale University, New Haven, Connecticut; [2]Division of Engineering, Brown University, Providence, Rhode Island.

We report on the performance of AlInGaN LEDs, aimed at high power operation in the 330 nm wavelength range. Quaternary AlInGaN multiple quantum well active regions are embedded into AlGaN p-n diodes, which are grown on AlN buffer layers on c-axis sapphire substrates. Circular devices with diameters of 100 um and below have been evaluated, with emphasis on testing the performance limits in the high power, pulsed injection regime. Under CW conditions, typical internal radiative efficiencies exceeding two percent have been achieved from LEDs that show clean emission spectra centered around 330 nm, with residual longer wavelength (defect and/or leakage mediated) emission one to two orders of magnitude smaller. The robustness of the devices has been verified under pulsed injection (10 nsec-1 μsec) at current densities in excess of 10 kA/cm2 where UV output power densities directly off a planar device chip up to tens of Watts/cm2 have been measured. Both growth and device design parameters affecting LED performance will be presented. As application demonstration, we will report on time resolved measurements of fluorescence lifetime of NADH in solution form. Research supported by DARPA SUVOS program under SPAWAR Systems Center Contract No. N66001-02-C-8017.

11:30 AM Y1.9
Optical Properties of AlN/AlGa(In)N Short Period Superlattices - Deep UV Light Emitting Diodes and Photodetectors. Mark Holtz, I. Ahmad, V. Kuryatkov, B. Borisov, G. Kipshidze, A. Chandolu, S. A. Nikishin and H. Temkin; Texas Tech University, Lubbock, Texas.

We report electrical and optical properties of deep UV light emitting diodes (LEDs) and photodetectors (PDs). Devices are based on short period superlattices of AlN/Al xGa 1-x(In)N ($x \sim 0.08$) grown by gas source molecular beam epitaxy with ammonia. Structures consist of a 50-nm thick AlN nucleation/buffer layer deposited on sapphire. This is followed by a 1-micron thick Si-doped buffer layer of AlGaN or AlN/AlGa(In)N designed to be transparent for wavelengths longer than 240 nm. The design thickness of the superlattice well layers is systematically varied from 0.50 nm to 1.25 nm and the thickness of the barrier is varied from 0.75 nm to 2.00 nm. The n- and p-type SPSLs were doped with Si derived from silane and Mg evaporated from an effusion cell, respectively. Optical properties are investigated using reflectance, cathodoluminescence, and, in the case of LEDs, using electroluminescence. By controlling the properties of the superlattice, we obtain energy gaps ranging from 4.5 eV (276 nm) and 5.3 eV (234 nm). Electrical properties are studied using I-V, C-V, and Hall effect. LEDs based on these superlattices and operating in the range of 260 to 280 nm exhibit turn-on voltages in the range of 4 to 6 V and support dc current densities in excess of 500 A/cm2 at room temperature. The cutoff wavelength of PDs based on these SPSLs can be varied in the range of 247 to 260 nm by changing the barrier and well thicknesses. We present results on the electrical and optical properties of our LEDs and PDs designed based on these studies. Influence of barrier/well thickness variations on the output power of LEDs will be also discussed. This work is supported by DARPA, NSF (ECS-00700240 and ECS-9871290), US Army SBCCOM, and the J. F. Maddox Foundation.

11:45 AM Y1.10
High Performance Solar Blind Detectors based on AlGaN grown by MBE and MOCVD. Jean-Yves Duboz[1,2], Jean Luc Reverchon[2], Mauro Mosca[2], Nicolas Grandjean[1] and Franck Omnes[1]; [1]CRHEA-CNRS, Valbonne, France; [2]Device Department, Thales TRT, Orsay, France.

Solar blind detectors based on AlGaN were fabricated and characterized. AlGaN heterostructures, with an active region with 43% Al and a window layer with 63% Al were grown on sapphire to allow for back side illumination. Both Molecular Beam Epitaxy and Metal Organic Chemical Vapor Deposition were used and led to similar results. Metal-Semiconductor-Metal (MSM) and Schottky diode detectors have been fabricated. Photoresponse spectra were recorded and show solar blind characteristics with cut off wavelengths in the range of 270-290 nm. The visible and near UV rejection ratio reaches 5 decades and the cut off slope is 4 nm per decade, which is the current state of the art for solar blind detectors. In MSM detectors, we used a two-level process where the contact pads are reported on a dielectric layer which allows to reduce the dark current to values as small as 10-100 fA for biases up to 20V in a detector with a 2 mm finger spacing and an area of 100mmx100mm. The noise is below the detection limit. Extrapolations can be made from measurements performed at higher biases or on devices with larger dark currents. They show that the noise is limited by the shot noise. The responsivity is in the range of 0.05 to 0.1 A/W. At 10V, the dark current is about 1 fA, and the noise density is 1.8E-17A/sqrt Hz. For a band width of 50 Hz, the noise current is thus 1.25E-16 A. With a responsivity of 0.05 A/W, the detectivity D equals 4E14 /W corresponding to a noise equivalent power NEP=2.5 fW. This corresponds to a photon flux of 500/s per pixel which is among the best values ever reported in AlGaN solar blind detectors. The effect of the geometry (finger spacing and width) was studied, and we will use it to show the ultimate performance that can be obtained in AlGaN MSM detectors. Schottky diode AlGaN solar blind detectors exhibit a larger dark current due to parasitic leakage currents on the mesa edges. They however show a larger responsivity, so that high perfomance is also achieved in AlGaN solar blind Schottky diodes.

SESSION Y2: Bulk/Quasi Substrates
Chair: Richard Molnar
Monday Afternoon, December 1, 2003
Room 312 (Hynes)

1:30 PM Y2.1
Growth and Fabrication of 2 Inch Free-standing GaN

Substrates Via the Boule Growth Method. Drew Hanser, Lianghong Liu, Ed Preble, Darin Thomas and Mark Williams; Kyma Technologies, Inc., Raleigh, North Carolina.

High quality, single crystal GaN substrates have been demonstrated using a boule growth process. Here we report on the crystalline boules that were formed during the growth process and their material characterization. Using a chemical vapor transport process, GaN crystals were grown at growth rates greater than 200 μm/hr. Boules greater than 3 mm thick were grown and processed into free-standing substrates. Rocking curve measurements using high-resolution X-ray diffraction were performed on the substrates with FWHM values of 92 and 146 arcsec for the (002) and (102) reflections, respectively. Transmission electron micrographs of the GaN material show high quality material quality with a dislocation density in the range of 5×10^6 cm^{-2}.

1:45 PM Y2.2
Post-growth Wafering and Surface Preparation Processes for 2 Inch GaN Substrates: Characterization of Surface and Material Properties. Mark Williams, Lianghong Liu, Ed Preble, Darin Thomas and Drew Hanser; Kyma Technologies, Inc., Raleigh, North Carolina.

Free-standing 2 inch GaN substrates fabricated via the boule growth method were processed to prepare for epitaxial growth. We report here on the post-growth wafering and polishing process and the characterization of the substrate surfaces. A combination of mechanical polishing, chemical mechanical polishing (CMP), and plasma etching were used to create a flat, damage-free surface. Cross-sectional TEM images and photoluminescence measurements indicate the presence of surface damage after mechanical processing, which is not effectively removed with a CMP process. ICP etching was used to remove the surface damage and create a surface suitable for epitaxial growth. Atomic force microscope images show a surface roughness RMS value of 1 nm and a peak-to-valley value of < 15 nm, both of which approach values for commercially available sapphire wafers.

2:00 PM Y2.3
Growth and Characterization of Bulk GaN Crystals at High Pressure and High Temperature. Mark P D'Evelyn[1], Huicong Hong[1], Dong-Sil Park[1], Kristi J Narang[1], Steven F LeBoeuf[1], Philip R Taverner[2], David R Clarke[2] and Richard J Molnar[3]; [1]GE Global Research Center, Niskayuna, New York; [2]Materials Department, University of California, Santa Barbara, Santa Barbara, California; [3]Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts

We report the growth and characterization of bulk GaN single crystals by temperature-gradient recrystallization at high pressure and high temperature (HPHT), using apparatus adapted from that used to synthesize gem-grade diamond crystals. The bulk crystals are grown on seeds that were synthesized by hydride vapor phase epitaxy (HVPE) and subsequently removed from their sapphire substrate. The process is routinely able to grow crystals larger than 10×10 mm in diameter. The crystals are transparent and well faceted, and dislocation densities below 10^4 cm^{-2} have been achieved. Additional characterization of the GaN crystals is also presented.

2:15 PM Y2.4
Free-standing A-plane Gallium Nitride Fabricated via Spontaneous Lift-off. Benjamin Allen Haskell[1,2], Shigemasa Matsuda[1], Tetsuo Fujii[1], Feng Wu[1,2], Paul T Fini[1,2], Steven P DenBaars[1,2], James S Speck[1,2] and Shuji Nakamura[1,2]; [1]Materials Department, University of California, Santa Barbara, California; [2]NICP/ERATO JST, UCSB Group, University of California, Santa Barbara, California.

Nonpolar (11-20) a-plane gallium nitride has been found to grow heteroepitaxially on (1-102) r-plane sapphire by a number of groups. However, previous attempts to grow a-plane GaN on r-plane Al_2O_3 by hydride vapor phase epitaxy (HVPE) yielded faceted films that were unsuitable for subsequent device regrowth. Recently we reported on the first HVPE growth of planar a-plane GaN films on r-plane sapphire. These films were characterized by smooth surfaces with RMS roughness values below 0.8 nm, but decorated by $\sim10^9$ cm^{-2} nanometer-scale pits and ridges marking threading dislocation terminations and basal plane stacking faults, respectively. In this abstract, we report on lateral epitaxial overgrowth (LEO) of a-plane GaN, its effectiveness in eliminating both threading dislocations and basal plane stacking faults, and subsequent substrate removal via spontaneous lift-off. The a-plane GaN LEO growth process was performed in a three-zone directed-flow HVPE system at 1040-1070°C. Typical growth rates were 16-50 μm/hr with V/III ratios of 15-30. The masks for the LEO process were prepared by utilizing conventional photolithographic processing and wet etching to ~130 nm-thick plasma-enhanced chemical vapor deposited SiO_x dielectric layers. A variety of mask geometries were found to yield planar, coalesced films, including arrays of parallel stripes oriented along the GaN <1-100>, <1-102>, and <0001> directions. In each case, atomic force microscopy showed a reduction of the surface pit density to less than 3×10^8 cm^{-2} and RMS roughness values below 0.7 nm. The overgrown material in the Ga-face (0001) wings for <1-100>-oriented stripes was found to have threading dislocation and basal plane stacking fault densities of less than the transmission electron microscopy resolution limits of 5×10^6 cm^{-2} and 3×10^5 cm^{-1}, respectively. Cathodoluminescence studies of the LEO films showed a four-fold increase in band edge luminous intensity in the overgrown material compared to the window material. The above-described LEO process has been utilized to fabricate free-standing a-plane GaN films for the first time through spontaneous lift-off. In addition to providing defect reduction, a-plane GaN films grown laterally from <1-102>-oriented stripes spontaneously separate from their substrates on cooling. Thermal expansion-related stresses bow the wafers to radii of curvature of less than one meter at room temperature. Virtually no adhesion exists between the laterally overgrown GaN and the mask material, and separation occurs consistently in the window material between the SiO_x stripes. The a-plane GaN films spontaneously peel off from the outer edges of the wafer inward to relieve the bowing stresses. Nearly full two-inch wafers have been produced by this process with film thicknesses of 125 μm by this process.

2:30 PM Y2.5
Selective Area Lateral Epitaxy of A-Plane GaN Layers and Heterostructures on R-Plane Sapphire. Changqing Chen, Jinwei Yang, jianping Zhang, wenhong sun, Mikhail Gaevski, edmundas kuokstis, Vinod Adivarahan, Shiva Rai, shuai wu, hongmei Wang, zheng Gong, Ming Su and M Asif Khan; Depart. of Elect. Engr., Uni. of South Carolina, Columbia, South Carolina.

To date nearly all nitride light emitters employ c-orientation heterostructures that possesses strong electrostatic fields parallel to the [0001] direction. These internal fields severely limit the luminescence due to band bending, which spatially separates the electron and the hole wave functions. In this work, we report an innovative selective area lateral epitaxy (SALE) approach to deposit high quality low defect density (11-20) GaN films on (1-102) (r-) plane sapphire substrates. The fully coalesced SALE a-plane GaN films exhibit smooth surface (RMS roughness of 0.45nm), superior structural quality (FWHM of (11-20) omega-scan of only 0.09 degree), as well as excellent optical quality (threshold for stimulated emission 100 kW/cm2). Non-polar AlGaN/GaN, InGaN/GaN as well as AlInGaN/InGaN multiple quantum wells were then grown on the SALE films. The light emission intensities from these heterostructures were at least one order of magnitude higher as compared to the MQWs which were deposited on the planar a-plane GaN films grown by the conventional MOCVD process. Therefore, our new SALE growth procedure provides an excellent approach for producing non-polar nitride films and heterostructures for high efficiency optoelectronic devices.

2:45 PM Y2.6
Recent results on vapor phase epitaxial and bulk growth of GaN and AlN materials. Vladimir A Dmitriev, Yuri V Melnik, Alexei Pechnikov, Oleg Kovalenkov, Vitali A Soukhoveev, Oleg Ledyaev, Vladimir Sizov, Yelyzaveta Shapovalova, Vladimir A Ivantsov and Alexander Usikov; TDI, Inc, Silver Spring, Maryland.

In this report we summarize our recent results on development of vapor phase crystal growth technique for group III nitride semiconductor materials. Material properties of GaN, AlN, and AlGaN epitaxial layers grown by hydride vapor phase epitaxy (HVPE) will be presented including properties of thick (up to 70 microns) crack-free AlN layers on 2-inch SiC substrates, AlN layers on 6-inch Si substrates, and GaN layers with reduced defect densities grown on 4-inch sapphire. Multi layer HVPE grown AlGaN/GaN- and AlGaN/AlGaN-based device structures for transistor and light emission applications in a wavelength range from 300 to 340 nm will be described. Second aspect of the report is growth and characterization of bulk single crystal materials from vapor phase. We will present the latest experimental data on material properties of GaN, AlN, AlGaN wafers fabricated from bulk crystals and initial results on homoepitaxial growth on these wafers.

3:30 PM Y2.7
AlN Crystal Growth by HVTE Using Metal-Organic Precursors. Vladimir Tassev[1], David Bliss[2], David Weyburne[2], John Bailey[1], Calvin Yapp[1], Ravi Kanjolia[3], Nam Nguyen[3], Lesley Smith[4], William Monk[4] and Raj Odedra[4]; [1]Solid State Scientific Corporation, Hollis, New Hampshire; [2]Air Force Research Laboratiory, Hanscom AFB, Massachusetts; [3]Epichem, Inc., Haverhill, Massachusetts; [4]Epichem, Inc., Bromborough, United Kingdom.

Aluminum nitride, because of its high thermal conductivity, UV transparency, and close lattice match to other III-nitride alloys, is of great interest for electronic and photonic applications. Large diameter single crystal AlN wafers have commercial potential as substrates for GaN and AlGaN based devices. However, the existing substrates are either too small in diameter or deposited on expensive non-native substrates, such as silicon carbide. The Halide Vapor Transport Epitaxial (HVTE) process, described here, was developed to overcome the present wafer deficiencies. To avoid the disadvantages of the conventional HVPE we have used $AlCl_3 - NH_3$, and $AlCl_3 - tBuNH_2$ adducts. By preforming the adduct, we reduce the reactivity and avoid many of the problems encountered in the typical VPE growth process. Sapphire templates with a 1μm thin AlN MOCVD layer are used to seed the HVTE growth. The influence of the deposition and adduct temperature, reactor pressure and gas flow velocities on the layer growth rate and crystal quality was investigated. The ranges of interest were mainly the high deposition temperatures (1000-1300°C), the low reactor pressure (1-50 Torr) and a range of total gas flow from 300 to 400 sccm. Single crystal AlN layers 2 inches in diameter and with thickness up to 50 μm have been grown with a deposition rate of 10-20 μm/h. The layer quality, as determined by x-ray rocking curve measurements (with a high resolution Philips instrument using omega scan), will be discussed. The FWHM for (002) and (102) planes are in the range of about 300 and 500 arc-sec, respectively, replicating the linewidths of the MOCVD templates. With trace element impurity measurements by SIMS analysis indicated about $10^{19}/cm^3$ oxygen and a negligible carbon contamination, the electrical properties remain insulating. Tests are under way to evaluate this material as a substrate for GaN-based devices.

3:45 PM Y2.8
Vapor phase transport of AlN in an RF heated reactor: Low and high temperature studies. Vladimir Noveski[1,2], Raoul Schlesser[1], Zlatko Sitar[1], S. Mahajanb[2] and Stephen Beaudoin[3]; [1]Department of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; [2]Department of Chemical and Materials Engineering, Arizona State University, Tempe, Arizona; [3]School of Chemical Engineering, Purdue University, West Lafayette, Indiana.

AlN crystals were grown by vapor phase transport in an RF heated sublimation reactor. The studies were performed with two main goals: 1) to optimize the initial nucleation stage of single crystal growth on AlN-coated SiC (seeded growth), and 2), to improve the growth rate by investigating the mass transfer effects in the high temperature range from 2000-2400°C. The effects of temperature, source-to-seed distance and the growth time in the lower temperature range were investigated. A one-dimensional mass transfer model based on equilibrium sublimation and gas-phase diffusion was developed. Model parameters were estimated from growth experiments carried out at a nitrogen pressure of 600 Torr, a nitrogen flow-rate of 100 sccm and temperatures from 2000 to 2250 °C. The model was validated against independent growth experiments conducted between 2200 and 2400 °C, with growth rates of 1 mm/hr of 25 mm diameter and 12 mm long polycrystalline boules. The seeded growth nucleation studies were conducted at temperatures ranging from 1800 to 2000 °C, while all other parameters were the same as in the high temperature studies. At lower temperatures (1800-1850 °C) and large source-to-seed distance (~35 mm), discrete single crystal growth was observed with few instances of coalescence. Higher temperatures (1900 °C), short source-to-seed distances (~10 mm) and longer growth times (~30 hrs) yielded better crystal coalescence. After the nucleation stage, the observed growth rates were in agreement with the predictions of the growth model developed above for gas-phase mass-transfer controlled growth of polycrystalline boules. Optical and electron microscope images of the seeded crystals revealed step-flow growth while the x-ray analysis confirmed the single crystalline nature of the grown material. Transparent and essentially colorless single crystalline AlN was grown over surface areas of 200-300 mm^2.

4:00 PM Y2.9
Influence of Crucibles on AlN Bulk Crystal Growth. Rafael Dalmau, Raoul Schlesser and Zlatko Sitar; Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

Growth of AlN bulk single crystals by sublimation of AlN powder was carried out in a resistively heated reactor at temperatures up to 2300 °C. Experiments were performed in nitrogen atmosphere at pressures ranging from 400 to 600 Torr and 100 sccm gas flow. A variety of crucible materials, such as BN, AlN, W, Ta, TaN, and TaC, were evaluated. Our studies have shown that the morphology of crystals grown by spontaneous nucleation strongly depends on the growth temperature and contamination in the reactor. Crucible selection had a profound effect on contamination in the crystal growth environment, influencing nucleation, coalescence, and crystal morphology. Crystals grown in BN crucibles exhibited highly anisotropic growth rates along different crystallographic directions. Crucibles made of refractory metals, and metal carbides or nitrides, yielded well-faceted crystals with isotropic growth rates. Depending on the choice of reaction crucible, crystals were optically clear or tinted orange. Orange coloration was observed in crystals grown in refractory metal crucibles. Spontaneously grown single crystals up to 15 mm in size were characterized by x-ray diffraction (XRD), transmission electron microscopy, x-ray topography, and SIMS. Average dislocation densities were on the order of $1000/cm^2$, with extended areas virtually dislocation-free, while high-resolution XRD showed rocking curves as narrow as 7 arcsec. A survey of the influence of reaction crucibles on crystal growth and morphology, as well as characterization data, will be presented.

4:15 PM Y2.10
Growth of GaN crystals under ammonothermal conditions. Buguo Wang[1], Michael J. Callahan[2], David F. Bliss[2] and Joseph W. Kolis[1]; [1]Department of Chemistry, Clemson University, Clemson, South Carolina; [2]SNHC, Air Force Research Laboratory, Hanscom AFB, Massachusetts.

Growth of GaN bulk crystals under ammonothermal conditions have been developed. The experiments were performed at 500 - 600 °C, 30 ~ 45 kpsi from ammonobase solutions in René autoclaves for up to 3 weeks. Nutrients were polycrystalline GaN made from vapor phase transport growth. Single crystal clusters of GaN on the order of 500 μm - 1 mm long were obtained. These crystals were spontaneously nucleated on the lower walls of the autoclaves. Transported growth on polycrystalline seeds from vapor growth at up to 100 μm per day was also achieved. The ammonothermal growth of GaN on HVPE single crystal seeds is under investigation. GaN has a high solubility in ammonobase solutions, but the dissolving process is slow and intermediate species formed from GaN dissolution have high stability at low temperatures. The intermediates have been characterized by XRD, FTIR and chemical analysis. The ammonothermal crystals were characterized by photoluminescence (PL), XRD and SEM. The high quality crystals with well-defined morphology have been verified by PL and X-ray diffraction. The growth mechanisms will be discussed.

4:30 PM Y2.11
Curvature and strain in thick HVPE-GaN for quasi-substrate applications. Claudia Roder[1], Tim Boettcher[1], Detlef Hommel[1], Tanya Paskova[2] and Bo Monemar[2]; [1]Inst. of Solid State Physics, University of Bremen, Bremen, Germany; [2]Department of Physics and Measurement Technology, Linkoeping University, Linkoeping, Sweden.

In order to overcome the major problem in the GaN technology, namely the lack of a native substrate, the most promising approach is the fabrication of thick GaN on sapphire utilizing hydride vapor phase epitaxy. In combination with the laser lift-off technique, free-standing GaN films were demonstrated. However, a critical remaining question arising from the thermal and the lattice mismatch is the accumulation of strain and wafer bending during growth and during cooldown, since both can cause the cracking of the film and the sapphire. To access the strain state at room and at growth temperature, temperature-dependent X-ray diffraction up to 1000 Kelvin was utilized to determine the lattice constants as well as the wafer curvature simultaneously. The combination allows to separate the individual strain components, namely the extrinsic, thermal strain as well as the intrinsic growth and hydrostatic strain. In agreement with previous findings, all samples investigated were found to be under biaxial tension at growth temperature, which is presumably caused by the high-temperature island coalescence. Upon cooldown, the thermal strain overcompensates the intrinsic, growth strain, such that at room temperature the film is under biaxial compression, while the substrate is tensile strained. In addition, the wafer bending amplifies the tension at the GaN-sapphire interface, such that at a critical thickness cracks nucleate due to the low tensile strength of sapphire. One solution is to increase the thickness of the sapphire substrate, which reduces the wafer bending and raises the critical thickness for crack appearance. To quantify the hydrostatic strain, GaN layers of varying thickness grown on sapphire as well as free-standing GaN were measured, since a gradient of the hydrostatic strain might explain the curvature of free-standing material after lift-off. All measurements are in good agreement with quantitatvie simulations of the stresses at the various interfaces.

4:45 PM Y2.12
Dislocation dynamics in laterally-grown GaN beyond dislocation bending. Andrew Y Kim[1], Werner Goetz[1], Junko Kobayashi[1], Mike Krames[1], Rick Mann[1], David Follstaedt[2], Nancy Missert[2], Paula Provencio[2], Daniel Koleske[2], Christine Mitchell[2], Katherine Bogart[2] and Andrew Allerman[2]; [1]R&D, Lumileds Lighting, US, LLC, San Jose, California; [2]Sandia National Laboratories, Albuquerque, New Mexico.

Lateral growth of GaN is used in a variety of related techniques to produce lower dislocation densities than currently possible with direct GaN growth onto sapphire or silicon carbide. Research has focused on bending dislocations from initial GaN growth into the substrate plane where they are presumably annihilated, terminate at a free surface, or are at least concentrated into initial growth and coalescence regions. It has also been noted that wing tilts result in tilt boundaries of dislocations upon wing coalescence, which could be a substantial source of dislocations in otherwise high-quality materials. In this report, we discuss the dislocation dynamics occuring after dislocation bending in cantilever epitaxy materials. Secondary networks of dislocation are observed to form what are believed to be tilt boundaries necessary to accommodate wing tilt, or in some cases are distributed throughout the wings to create wing curvature. The observed number of dislocations is generally insufficient to fully account for the wing tilts, i.e. some of the wing tilt is accomodated elastically. In samples with wing tilts ranging from 0.2 to 2 deg, the elastic tilt is estimated to be ~0.15 deg. We propose a model analagous to the critical thickness in lattice-mismatched epitaxy, where there is a critical tilt that is always accomodated elastically. The model suggests that tilt boundary dislocations can be avoided altogether if the wing tilts can be reduced below the critical tilt. Another source of secondary dislocations are defects in the wing coalescence interfaces that punch out dislocation loops in the c-plane. The threading dislocations over cantilever 'posts' have been observed to pin dislocation loops, i.e. we propose that the Cottrell mechanism acts to limit the size of the dislocation loops. The strength of the Cottrell mechanism in limiting dislocation loops decreases as the density of the 'forest' of perpendicular threading dislocations decreases, which may explain why dislocation loops can be very large in samples with otherwise very low dislocation density. Elimination of both types of secondary dislocations is of interest for practical device applications: tilt boundary dislocations occur in every wing and dislocations loops, while they may appear infrequent on the microscale, can represent a substantial defect density on the scale of a modern GaN device. These models for dislocation dynamics are not specific to cantilever epitaxy and should apply to other techniques using lateral growth of GaN. Therefore, reducing wing tilts to below a critical tilt and eliminating the formation of dislocation loops at the wing coalescence interfaces are two important challenges to obtaining truly low dislocation density in laterally-grown GaN devices.

SESSION Y3: Heteroepitaxy
Chair: Theodore Moustakas
Tuesday Morning, December 2, 2003
Room 312 (Hynes)

8:30 AM *Y3.1
GaN-based epitaxy and devices on Silicon. Alois Jakob Krost, [1]Institute of Experimental Physics, Otto-von-Guericke Universitaet Magdeburg, Magdeburg, Germany; [2]Otto-von-Guericke Universitaet Magdeburg, Magdeburg, Germany.

Since 15 years silicon as a substrate has attracted much attention for the epitaxial growth of III-V compounds like GaAs and InP because of its unique physical properties, low price and its availability in large diameters up to 12 inches now. From the point of view of economics Si offers a low price as compared to sapphire and SiC, high crystalline perfection, availability of large size substrates, all types of conductivity, and high thermal conductivity. Furthermore, it can be easily processed. However, in spite of huge efforts, no real breakthrough has been obtained because of the high mobility of dislocations in GaAs and InP leading to a rapid degradation of all devices fabricated so far. In contrast, GaN-based devices are known to operate very well without aging effects with dislocation densities as high as 1010 cm-2. Thus, in case of a successful growth of GaN on Si, GaN-based electronics and optoelectronics as well as the integration of Si- and GaN-based devices on the same chip becomes feasible. The growth of device-quality GaN on Si is known to be limited by severe stress problems leading to a wafer bending and to cracked layers when exceeding ~1 micrometer in thickness. Using an in-situ optical sensor for monitoring the wafer curvature we distinguished and controlled several origins of residual stresses during growth: epitaxial streses due to misfit of interatomic distances, e.g. compressive when inserting an AlN interlayer, thermal stresses due to the difference between the film and substrate thermal expansion coefficients (tensile), Si- and Mg-doping (tensile), grain boundary relaxation during coalescence of 3D islands (tensile), insertion of sub-monolayer SiN masks (compressive). Remarkably, the strong tensile stress for Si-doped GaN cannot be explained by a simple change of interatomic distances but is likely correlated to the dislocation density. By an appropriate balance of all these contributions cracking and bowing of the substrates can be avoided. With the insertion of thin AlN interlayers and in-situ SiN nanomasks, we succeeded in growing 4 micrometer thick, crack-free, planar GaN on Si. Latest results on FET and LED device structures based on such layers will be presented.

9:00 AM Y3.2
Achieving High Quality AlN Epilayers: Epitaxial Growth, Optical Transitions, and Impurity Properties. Mim Lal Nakarmi, Ki-Bum Nam, Neeraj Nepal, Jing Li, Kyoung Hoon Kim, Jingyu Lin and Hongxing Jiang; Physics, Kansas State University, Manhattan, Kansas.

Knowledge concerning the optical properties of AlN is very scarce, despite its importance for the fundamental understanding of wide band gap semiconductor properties as well as for device applications. With its large direct bandgap (around 6.1 eV at room temperature), high thermal conductivity and hardness, and high resistance to chemicals, AlN has many attractive properties and many important applications such as UV emitters for the detection of biological and chemical agents and for general lighting. Here, we report the MOCVD epitaxial growth and deep UV time-resolved photoluminescence (PL) studies of high quality AlN epilayers. Important parameters including the energy bandgap, the free and bound exciton binding energies and decay lifetimes have been measured. Mg and Si doping in AlN was attempted. From PL emission spectra and the temperature dependence of the PL emission intensity, a binding energy of 0.51 eV for Mg acceptor in AlN was determined. Together with previous experimental results, the Mg acceptor activation energy in AlxGa1-xN as a function of the Al content (x) was extrapolated for the entire AlN composition range. The average hole effective mass in AlN was also deduced to be about 2.7m0 from the experimental value of the Mg binding energy together with the use of the effective mass theory (assuming a dielectric constant of 8.5). Although Mg acceptors are an effective mass state in ultra-large bandgap AlN, as a consequence of this large acceptor binding energy of 0.51 eV, only a very small fraction (about 10-9 or one billionth) of Mg dopants can be activated at room temperature in Mg doped AlN, implying that it is extremely difficult to achieve p type AlN by Mg doping. Si doping induced PL emission linewidth broadening and band gap renormalization effects have also been observed. The role of oxygen impurities in determining the optical and electrical properties AlN has been investigated.

9:15 AM Y3.3
HNO_3 treatment of sapphire substrate for management of GaN polarity in MOCVD method. Motoki Takabe[1], Masatomo Sumiya[1,2] and Shunro Fuke[1]; [1]E&E Eng, Shizuoka University, Hamamatsu, Japan; [2]CREST-JST, Tokyo, Japan.

We discovered that HNO_3 treatment of a c-plane sapphire substrate led to management of the polarity of GaN film grown by MOCVD. A sapphire substrate was treated in HNO_3 solution at room temperature after cleaning it in H_2-flow at 1080°C. When GaN film was grown on the treated substrate by conventional two-step growth in MOCVD, it had N-face (-c) polarity, having hexagonal facetted surface. GaN film grown on a H_2-cleaned substrate without the HNO_3 treatment had Ga-face (+c) polarity, having smooth face, even though the substrate was exposed to air. By using this treatment, we have attempted simultaneous growth of GaN film with both polarities (+c,-c) on divided area of a sapphire substrate. After the H_2 cleaning in the growth reactor, a mask pattern of photoresist was formed on the H_2-cleaned substrate, and then it was dipped in HNO_3 solution for 10 min. After removing the mask pattern, the substrate was introduced into the reactor again, and GaN film was deposited on it by two-step MOCVD method. GaN film with hexagonal facet and smooth surface in the other region were simultaneously grown on HNO_3 treated and the other region of the substrate, respectively. It was confirmed that only region of hexagonal facet was etched by KOH solution. We achieved successfully the simultaneous growth of GaN film with both polarities. This indicated that the position of polarity-controlled GaN film would be managed on a sapphire substrate.

9:30 AM Y3.4
Step-Flow and Layer-by-Layer Growth of AlN on SiC (0001) by Molecular-Beam Epitaxy. Jun Suda[1,2], Norio Onojima[1], Tsunenobu Kimoto[1] and Hiroyuki Matsunami[1]; [1]Department of Electronic Science & Engineering, Kyoto University, Kyoto, Japan; [2]"Nanostructure and Material Property", PRESTO, Japan Science and Technology Corporation (JST), Kawaguchi, Japan.

Growth of high-quality AlN on a SiC substrate is one of key issues to realize high-performance GaN-based high-power high-frequency heterojunction field-effect transistors (HFETs) and AlN/SiC metal-insulator-semiconductor FETs (MISFETs). We have investigated precise control of SiC (0001) surface and optimization of growth conditions of AlN in molecular-beam epitaxy (MBE). Recently, we have realized RHEED intensity oscillation just after the growth of AlN on SiC with high reproducibility [1]. In this study, we focused on the correlation between growth kinetics and crystalline quality of AlN grown layer. 4H- or 6H-SiC (0001) on-axis substrates were processed by high-temperature HCl-gas etching to remove a surface damaged

layer and obtain 4 ML or 6 ML-height step-and-terrace structure. Next, substrates were dipped into HF solution for oxide removal and then loaded into an MBE system. Before the growth, in-situ Ga-deposition and flush-off were carried out, which results in an oxygen-free ($sqrt3 \times sqrt3$)R30° surface. AlN was grown by rf plasma-assisted MBE. Growth at a high temperature (1000°C): RHEED intensity oscillation indicating layer-by-layer growth of AlN lasted only 5 to 6 cycles, followed by step-flow growth confirmed by AFM measurements. The growth mode transition originates from dissolving of 4 ML or 6 ML-height step into 1 ML-height step. Growth at a low temperature (600°C): RHEED intensity oscillation lasted over 60 cycles, indicating that AlN grew in layer-by-layer mode all thorough the growth. A low-temperature growth leads higher super saturation and/or shorter migration length, which resulted in such a growth mode. Symmetrical (0002) and asymmetrical (01-14) X-ray rocking curve measurements were carried out for evaluation of crystalline quality. For (0002) diffraction, both high-temperature and low-temperature grown layers showed almost the same FWHM values (70 arcsec for 100 nm-thick AlN). On the other hand, for (01-14) diffraction, the FWHM of low-temperature grown AlN was much smaller (180 arcsec) than that of high-temperature grown AlN (450 arcsec). These results suggests that layer-by-layer growth resulted in reduction of twisting or edge-type dislocations. [1] N. Onojima, J. Suda and H. Matsunami, Jpn. J. Appl. Phys. 42 (2003) L445.

9:45 AM Y3.5
Growth and Surface Reconstructions of AlN(0001) Films.
Chae-Deok Lee[1,4], Randall M Feenstra[1], John E Northrup[2] and Joerg Neugebauer[3]; [1]Physics, Carnegie Mellon Univ., Pittsburgh, Pennsylvania; [2]Palo Alto Research Center, Palo Alto, California; [3]Fritz-Haber-Institut der Max-Planck-Gesellschaft, D-14195 Berlin, Germany; [4]Raytheon RF Components, Andover, Massachusetts.

AlN is considered to be a useful semiconductor material for high temperature and high power electronic devices and also optoelectronic device applications. While there has been progress in identifying surface structural arrangements on GaN, there is currently only limited knowledge of the surface structures of AlN. Therefore, we have performed experimental and theoretical studies of the surface reconstructions of AlN films. The AlN films are grown on Si-face 6H-SiC substrates or MOCVD-grown GaN(0001) templates by plasma-assisted molecular beam epitaxy to obtain Al polarity. For moderately Al-richr surfaces, surface reconstructions with symmetry of $2sqrt3 \times 2sqrt3$-R30° and $5sqrt3 \times 5sqrt3$-R30° are found on the basis of scanning tunneling microscopy (STM) and low-energy electron diffraction observations. Such surfaces display a predominantly 2x6 pattern in reflection high-energy electron diffraction. Auger electron spectroscopy indicates an Al coverage for such surfaces of 2-3 monolayers. Based on this result and on first principles total energy calculations it is argued that these reconstructions involve a laterally contracted Al adlayer structure similar to that previously proposed for GaN(0001). At higher Al coverages a thick, flat Al film is found to form on the surface. For Al-poor conditions, additional surface reconstructions with $sqrt3 \times sqrt3$-R30° and 2x2 periodicities are observed. For growth temperatures of 750-800°C a large number of growth spirals (about $3x10^9$ cm^{-2}) are seen in the large-scale STM images. These spirals are indicative of threading dislocations having a screw component. For higher growth temperatures of 850-880°C the number of screw dislocations in the film is found to be significantly reduced, to about $3x10^8$ cm^{-2}. This work has been supported in part by the Office of Naval Research under grants N00014-02-1-0933(C. Wood) and N00014-02-0433(L. Cooper).

10:30 AM *Y3.6
High-Quality AlN Epitaxial Films Grown using MOVPE and Their Applications.
Mitsuhiro Tanaka[1], Tomohiko Shibata[1,2], Keiichiro Asai[1], Shigeaki Sumiya[1], Masahiro Sakai[1], Hiroyuki Katsukawa[1], Osamu Oda[1], Hideto Miyake[2], Kazumasa Hiramatsu[2], Hiroyasu Ishikawa[3], Takashi Egawa[3], Takashi Jimbo[3] and Shigefusa Chichibu[4]; [1]NGK INSULATORS, Nagoya, Japan; [2]Mie University, Mie, Japan; [3]Nagoya Institute Technology, Nagoya, Japan; [4]Tsukuba University, Tsukuba, Japan.

AlN has piezoelectricity and the widest direct band gap (6.2eV) of the III-V nitride materials, so that the realization of high-quality AlN epitaxial films can widely extend application fields of III-V nitride materials. So far, we have been growing AlN epitaxial films on several single-crystalline substrates using metal organic vapor phase epitaxy (MOVPE) for various applications including surface acoustic wave (SAW) devices, optoelectronic devices and electronic devices. In order to realize SAW devices, a (11-20)-faced AlN epitaxial film on a (10-12)-faced sapphire substrate is the most promising combination due to its modest electromechanical coupling coefficient (1%) and its high SAW velocity (6000m/sec). Using off-angle sapphire substrates, in which their surface plane is tilted towards [1-101] sapphire direction, have effects of improving AlN crystal qualities and arranging AlN polarity. As a result, 2.4GHz SAW filters can be reliably realized using the AlN films on the off-angle sapphire substrate. (0001)-faced AlN epitaxial films on (0001)-faced sapphire or 6H-SiC substrates have a great potential as templates for AlGaN growth, which can be applied to wide range of semiconductor devices. We have achieved crackless high-quality AlN epitaxial films with an atomically flat surface on both substrates. The AlN epitaxial films have narrow X-ray rocking curve (XRC) profiles for (0002) plane that correspond to full width at half maximum (FWHM) values equal to less than 100 arcsec. Dislocation density of the AlN epitaxial films is as low as $1x10^{10}$ /cm^2 and most of dislocations consist of edge-type ones. XRC FWHM values for (0002) plane of AlGaN epitaxial flms overgrwn on the AlN epitaxial films are equal to less than 200 arcsec and the AlGaN films have no cracks in all AlN molar fraction range. In particular, dislocation density in overgrown GaN reaches as low as $5x10^7$/cm^2. The improvement of crystal qualities of the overgrown AlGaN results in improving some device performance, such as luminous efficiency of LED, electronic properties of HEMT devices and so on.

11:00 AM Y3.7
Growth Evolution of Gallium Nitride Films on Stepped and Step-Free Silicon Carbide Surfaces.
C. R. Eddy[1], J C Culbertson[1], M E Twigg[1], R T Holm[1], R L Henry[1], P G Neudeck[2], A J Trunek[3] and J A Powell[4]; [1]Electronic Science & Technology Division, U.S. Naval Research Laboratory, Washington, District of Columbia; [2]NASA Glenn Research Center, Cleveland, Ohio; [3]OAI, NASA Glenn Research Center, Cleveland, Ohio; [4]Sest, Inc., NASA Glenn Research Center, Cleveland, Ohio.

Silicon carbide (SiC) is rapidly becoming the substrate of choice for the development of high frequency and high power electronic devices employing the III-V nitride family of materials. This heteroepitaxial growth system continues to receive considerable attention as materials issues remain the fundamental limiters to device performance. The heteroepitaxial growth of gallium nitride (GaN) thin films on stepped and step-free 4H SiC surfaces is reported. Step-free SiC surfaces are created by mesa patterning of a SiC wafer and subsequent epitaxial growth in a process described previously [1]. This process results in a collection of both step-free and stepped surfaces on a given sample. We have employed an established metalorganic chemical vapor deposition process to grow first a thin (120 nm) aluminum nitride (AlN) nucleation layer and then a 2 micrometer GaN thin film. We have interrupted growth at various stages of AlN and GaN growth to evaluate the growth evolution using atomic force microscopy (AFM). The results show marked differences in the manner in which the initial AlN layer deposits. Nucleation is random with elongated grains on step-free SiC surfaces, while stepped surfaces have round nuclei of uniform dimensions and a high degree of spatial correlation with the nuclei arranged in rows. These differences diminish as the AlN layer approaches the desired thickness. Growth of the GaN epilayer is also markedly different on the two types of surfaces with unstepped surfaces leading to random and low density nucleation of crystallites that remain as single grains for long growth times, whereas the stepped surfaces have large numbers nuclei that rapidly grow laterally. We will also report on evaluations of continuously grown layers of the same thicknesses (no interruption for AFM) and TEM analysis of both types of samples. [1] J. A. Powell, P. Neudeck, A. Trunek, G. Beheim, L. Matus, J. R. Hoffman, and L. Keys, "Growth of Step-Free Surfaces on Device-Size (0001)SiC Mesas," Applied Physics Letters, vol. 77, pp. 1449-1451, 2000.

11:15 AM Y3.8
GaN Nucleation Layer Evolution On Sapphire During The Ramp From Low To High Temperature.
Daniel D. Koleske, Michael E. Coltrin, Karen C. Cross, Christine C. Mitchell and Andrew A. Allerman; Org. 1126, Sandia National Laboratories, Albuquerque, New Mexico.

Despite the progress in the MOCVD growth of GaN, details on how the nucleation layer (NL) evolves during the ramp from low to high temperature (T) is not entirely understood. In this presentation in-situ optical reflectance and AFM measurements of stopped annealing experiments are used to study GaN NL evolution. During the T ramp and anneal, the NL morphology changes from a continuous 30 nm thick layer composed of 20 nm sized nuclei to a discontinuous layer containing nuclei that approach 200 nm in height and 500 nm in width. Further annealing of the NL causes a decrease in the size of these large nuclei. Since only NH3 and H2 are flowing during the NL annealing, the growth of these large GaN nuclei is explained by NL decomposition [1] and subsequent re-incorporation of the gas phase Ga atoms onto the growing nuclei. Evidence for this mechanism is obtained from the height-height correlation functions [2] measured from the AFM images of the annealed nucleation layers as well as direct measurements of the GaN NL decomposition kinetics using optical reflectance [1]. From the AFM images up to 1/3 of the Ga atoms from the original NL are redistributed into the large GaN nuclei during the T ramp, however once the original NL is fully

decomposed, the large GaN nuclei undergo decomposition resulting in smaller nuclei. Based on details of the decomposition kinetics and NL roughening, fits to the optical reflectance waveform will be presented. Contributions of the surface diffusion, bulk diffusion, and decomposition and re-incorporation mechanisms to GaN NL evolution will be discussed along with how annealing conditions influence the evolution process. Finally, guidance as to when the NL achieves optimal morphology for further GaN growth at high T will be presented. This work is supported by the Division of Materials Sciences and Engineering, Office of Basic Energy Sciences, U. S. Department of Energy, Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000. [1]. D. D. Koleske, et al., Appl. Phys. Lett 82, 1170 (2003). [2]. W. M. Tong and R. S. Williams, Annu. Rev. Phys. Chem. 45, 401 (1994).

11:30 AM Y3.9
ZnO/AlGaN heterojunction light emitting diodes.
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We report on the growth of n-type ZnO on p-type AlGaN and describe the performance of n-ZnO/p-AlGaN heterojunction light emitting diodes. Commercial n-type 6H-SiC wafers are used as substrates, as epitaxial GaN buffer layers and Mg doped p-type AlGaN epitaxial layers of 12% Al content are grown by hybrid vapor phase epitaxy. Then, Ga doped n-type ZnO layers are grown on the AlGaN using plasma assisted chemical vapor deposition. The heterojuction devices were fabricated by masking the surface, then 10% HNO3 aqueous solution is used to remove ZnO windows and leave regions of the AlGaN layer exposed. Ohmic contacts to the ZnO and AlGaN were made by thermal vacuum deposition of Al and Ni respectively. I-V characteristics clearly show rectifying "diode-like" behavior with a threshold voltage of 3.2 V and intense ultraviolet electroluminescence with peak emission at 390 nm, is observed under forward bias. The dominant emission mechanism is found to result from hole injection from the p-type, AlGaN into the n-type ZnO. This is a likely outcome since energy band diagrams built using the Anderson model show a much smaller barrier for holes in comparison to that which exists for electrons. The dependence of EL spectra on temperature was also measured and significant emission up to 500 K was observed. The stability of device performance at high temperature indicates possible applications in harsh environments. With further development, it may be possible to fabricate UV laser diodes, with low, "excitonic" thresholds and high-temperature capability, by exploiting the thermal stability of the ZnO exciton.

11:45 AM Y3.10
Electrical and optical characteristics of delta doped AlGaN cladding layer materials for highly efficient 340nm ultra violet LEDs. Houping P. Xin[1], Jeffrey Scott Flynn[1], Joe A. Dion[1], Edward L. Hutchins[1], Helder Antunes[1], Lara Fieschi-Corso[1], Rae Van-Egas[1], George R. Brandes[1], Steven LeBoeuf[2], Xian-An Cao[2], Jerome Garrett[2] and Larry Rowland[2]; [1]GaN Products, ATMI, Danbury, Connecticut; [2]General Electric Global Research Center, Niskayuna, New York.

Development of AlGaN-based high power output ultraviolet (UV) light emitting diodes (LED) have recently attracted renewed interest due to the need for bright, efficient UV sources for biochemical detection and solid-state white lighting. In this paper we report on the optical and electrical characteristics of delta doped AlGaN cladding layers and their impact on the efficiency of 340nm UV LEDs. The delta doped cladding layers and the multiple quantum well (MQW) UV LEDs examined in this study were grown on 2-inch c-plane sapphire at 1220oC in an Aixtron 200/4 MOCVD system using NH_3, TMGa, TMAl, Si_2H_6 and Cp_2Mg precursors. The UV LEDs consisted of n-$Al_xGa_{1-x}N$ cladding, an $Al_{0.1}Ga_{0.9}N/Al_{0.3}Ga_{0.7}N$ MQW active region and p-$Al_yGa_{1-y}N$ cladding. For this study, 1 μm thick n-$Al_{0.2}Ga_{0.8}N$ cladding uniformly doped with Si to $1x10^{18}cm^{-3}$ were compared to delta doped cladding with 3, 7 and 15 layers. The delta doped structures were doped to $1.0x10^{13}cm^{-2}$ in layers spaced 20 nm apart by stopping the flow of TMAl and TMGa. With the addition of three delta-doped layers, the sheet resistance was as low as 172±12 ohm cm^{-2} , a factor of three lower than the uniformly doped structure. Increasing the number of delta doped layers further lowered the sheet resistance of the n-layer and reduced the forward voltage of the devices. The delta doped layers also improved the optical properties of the cladding layers by enhancing near band edge emission as much as four-fold relative to deep level emission. Additionally, delta doping of the AlGaN layers had no detrimental effect on the optical transparency of the cladding layers in the LEDs with as high as 80% transparency for 20% n-AlGaN cladding. By optimizing the n- and p-AlGaN cladding layer doping, a highly efficient AlGaN active region 340nm UV LED was achieved with power output greater than 1.0mW under 800mA/mm^2 DC drive current. The optical and electrical characteristics of delta doped structures and devices will be further discussed.

SESSION Y4: Nanostructures
Chair: Yasuhiko Arakawa
Tuesday Afternoon, December 2, 2003
Room 312 (Hynes)

1:30 PM Y4.1
Effects of growth interruption on the structural and optical properties of GaN self-assembled quantum dots.
Katsuyuki Hoshino, Satoshi Kako and Yasuhiko Arakawa; Research Center for Advanced Science and Technology, and Institute of Industrial Science, University of Tokyo, Tokyo, Japan.

We report the effect of growth interruption on the formation of GaN self-assembled quantum dots (QDs) grown by metalorganic chemical vapor deposition (MOCVD). GaN QDs are expected to realize highly efficient UV light emitters, due to quantum confinement effect and dislocation free structure. The photoluminescence (PL) from the QDs showed a red-shift with increasing the growth interruption time. This indicates that the formation of the QDs is proceeding at the expense of the wetting layer (WL), which is supported by a blue-shift of the PL from the WL. These results show that the growth interruption plays an important role in the formation of the QDs. GaN self-assembled QDs were deposited on the top of AlN layers grown on 6H-SiC(0001) substrates. Following the GaN QD formation, the growth was interrupted from 0 to 10 sec (0, 2.5, 5, and 10 sec). Then, a 20-nm-thick AlN capping layer was deposited. Two PL peaks were clearly observed in each sample with the interruption process at room temperature. One peak occurs around 4.8 eV. This is considered to be due to the WL. The other occurs around 3.8 eV which originates from the QD structure. For no interruption time (0 sec), however, a strong single PL peak was observed at 4.1 eV. This peak can be attributed to the GaN quantum well signal. These results show that the two-dimensional/three-dimensional growth mode transition occurs during the initial growth interruption. The PL from the WL showed a blue-shift with increasing the interruption time. This implies that the thickness of the WL decreases. In contrast, the PL from the QDs exhibits a red-shift. These results mean that the size of the QDs increases at the expense of the WL, which is supported by AFM analysis of the uncapped QD samples.

1:45 PM Y4.2
Electron Field Emission from GaN Nanotip Pyramids Formed by Anisotropic Etching. Hock M. Ng[1], Jonathan Shaw[2], Aref Chowdhury[1] and Nils G. Weimann[1]; [1]Bell Labs, Lucent Technologies, Murray Hill, New Jersey; [2]Naval Research Laboratory, Washington, District of Columbia.

GaN is of interest as a candidate material for electron field emitters due to its large breakdown field, resistance to radiation and low electron affinity. In general, electron emitter structures with sharp tips are utilized to take advantage of the field enhancement effect. In this work, we formed GaN nanotip pyramids by polarity-selective chemical etching after a patterned growth of Ga- and N-polar GaN on (0001) sapphire using plasma-assisted molecular beam epitaxy. The anisotropic etch was achieved by immersing the sample in a KOH solution which preferentially etches the N-polar GaN leaving the Ga-polar material intact. Pyramidal structures with six {10-1-1} facets were formed in the N-polar regions. The density of the pyramids can be varied between 2×10^6 and 2×10^9 cm^{-2}, depending on the KOH concentration, etching duration and temperature. The tip diameters of the pyramids were measured to be less than 20 nm. Field emission measurements were performed in a vacuum chamber using a stainless steel rod as the anode. The anode to sample distance was varied between 350 to 650 μm. The resulting current-voltage curves fit well to the Fowler-Nordheim equation. The turn-on voltage was taken to be the voltage at which the total emission current was equal to 10 nA. The turn-on field was estimated to be 1.6 V/μm which is, to the best our knowledge, the lowest reported value for ungated GaN field emitters. The corresponding field enhancement factor was found to be 2200 ± 100 assuming a GaN work function of 3.5 eV. Results for lifetime measurements and cesiated GaN pyramids will also be presented.

2:00 PM Y4.3
Gallium Nitride Nanowires as Optoelectronic Devices.
John Jacob Zengel[1], R Gupta[2], K W Adu[2], C P Beetz[3] and P C Eklund[2,1]; [1]Materials Science & Engineering, The Pennsylvania State University, University Park, Pennsylvania; [2]Physics, The Pennsylvania State University, University Park, Pennsylvania; [3]NanoSciences Corporation, Oxford, Connecticut.

Long gallium nitride nanowires (dia. ~10nm) have been synthesized by pulsed laser vaporization of a solid target of GaN and well-dispersed Fe catalyst under 250Torr NH3 gas. The resulting materials were characterized by Raman spectroscopy, scanning and transmission electron microscopy, and energy dispersive X-ray to confirm that the individual nanowires are wurtzite GaN single crystals with a [100] growth direction and have diameters and lengths on the order of 10 nm and 10 μm, respectively. Various methods were employed to investigate the effect of geometry and electron confinement on the properties of GaN. Our results on Raman spectroscopy of GaN nanowires show that the Raman bands are broadened and downshifted as compared to the bulk. However, the size (diameter) of the nanowires is too large to exhibit any appreciable phonon confinement effects. We can understand our results in terms of other effects such as compressive/tensile stress. We also present results of other spectroscopic measurements such as FT-IR and UV/VIS transmission and photoemission.

2:15 PM Y4.4
Influence of AlN Overgrowth on GaN Nanostructures Grown by Molecular Beam Epitaxy. Noelle Gogneau, Eva Monroy, Denis Jalabert, Eirini Sarigiannidou, Jean Luc Rouviere and Bruno Daudin; DRFMC/SP2M/PSC, CEA - Grenoble, Grenoble, France.

The use of nanostructures in devices requires a precise control of the quantity of matter deposited, and of the quality of the interfaces. It is generally assumed that the growth rate of thick layers is not directly applicable in the nanoscale, where structures are particularly sensitive to decomposition, re-evaporation and diffusion. In the specific case of GaN nanostructures in AlN, the influence of overgrowth on the properties of nanostructures has not been addressed so far, although it is a crucial issue for the development of reproducible devices. In this work, we demonstrate that capping GaN nanostructures in an AlN matrix during Molecular Beam Epitaxy growth is associated with a remarkable change in the dimension of the nanostructures. Hence, the GaN quantum well thickness decreases during AlN overgrowth. Regarding GaN quantum dots, capping implies an isotropic reduction of the island size. The thickness/size reduction has been assessed by Rutherford Backscattering Spectroscopy (RBS) as a function of the GaN quantity. By combination of RBS, Transmission Electron Microscopy (TEM) and Reflection High Energy Electron Diffraction, we demonstrate that the reduction of the nanostructures occurs at the first stage of AlN overgrowth and it affects only the top GaN/AlN interface. The phenomenon is attributed to an exchange mechanism between Al adatoms from the cap layer and Ga atoms in the nanostructures. This process is favoured by the high binding energy of AlN as compared to GaN. We also demonstrate that this exchange is thermally activated and depends on the strain state of the nanostructures. Finally, the Ga from GaN decomposition behaves as a surfactant for AlN, and desorbs rapidly during the capping procedure. As a result, the interface between the GaN nanostructures and the AlN capping layer is abrupt, with an interdiffusion lower than one atomic layer, as measured from cross-section TEM images.

2:30 PM Y4.5
Intersubband Absorptions in Doped and Undoped GaN/AlN Quantum Wells Grown on Sapphire(0001), 6H-SiC or Silicon(111) Substrates. Ana Helman[1], Maria Tchernycheva[1], Alain Lusson[1], Francois Julien[1], Khalid Moumanis[1], Elias Warde[2], Eva Monroy[2], Bruno Daudin[2], Daniel Le Si Dang[2] and Nicolas Grandjean[3]; [1]Action OptoGaN, Institut d'Electronique Fondamentale, UMR8622 CNRS, Universite Paris-Sud, Orsay, France; [2]CEA/CNRS Research Group "Nanophysique et Semiconducteurs", DRFMC/SPMM, CEA/Grenoble, Grenoble, France; [3]CRHEA, UPR 10 CNRS, Valbonne, France.

Group III nitride heterostructures are triggering new interests because their huge conduction-band offset offers prospects for ultra-fast intersubband devices operating at fiber-optics telecommunication wavelengths. In recent works, room-temperature intersubband absorptions in the wavelength range of 1.1-4.5 μm as well as extremely short intersubband scattering times have been reported for n-doped GaN/Al(Ga)N quantum wells grown on sapphire substrate using molecular beam epitaxy. In this talk, we report on the first detailed analysis of intersubband absorptions (ISB) in non-intentionally-doped and doped GaN/AlN quantum wells grown by molecular beam epitaxy either on sapphire(0001), 6H-SiC or silicon(111) substrates. The samples have been characterized by X-ray diffraction, Rutherford back scattering (RBS) and high resolution transmission electron microscopy (TEM) as well as photoluminescence (PL) and Fourier transform infrared (FTIR) spectroscopy. We first illustrate the results for n.i.d. GaN wells with strained AlN barriers grown on sapphire substrate. Room-temperature photo-induced absorption spectroscopy under irradiation by a 305 nm argon laser reveals ISB absorptions respectively peaked at 2.1, 1.85 and 1.45 μm for samples with an average well thickness of 1.86, 1.26 and 0.7 nm, as deduced from RBS. Besides a larger broadening, similar results are obtained for samples grown on 6H-SiC or silicon substrates. Based on TEM and calculations, we show that strong electron localization occurs in the layer plane at room temperature due to the combined effect of monolayer (ML) thickness fluctuations and the huge internal field. More precisely, the thickness must be increased from the average value by 2 ML to account for the observed PL and ISB transition energies. Similar samples with GaN wells doped with silicon at $2x10^{19}$ cm^{-3} show an increased GaN growth rate with respect to n.i.d samples. The ISB absorption is peaked at 1.85, 1.7 and 1.45 μm for doped wells with an average thickness of 2.1, 1.35 and 0.91 nm, respectively. With respect to n.i.d. samples, both the increased thickness and the smaller internal field due to carrier screening should lead to a red-shift of the ISB transition energy, which is opposite to observations. In order to understand the blue-shift of the transitions with doping, we have simulated the electron confinement in the quantum wells using an effective mass approach accounting for the screened internal fields, the GaN conduction-band non-parabolicity and many-body effects such as the exchange interaction and the depolarization shift. For n.i.d. quantum wells, an excellent agreement with measurements is obtained assuming a GaN/AlN conduction band discontinuity of 1.78 eV and a polarization discontinuity of $\Delta P/\epsilon = 8$ MV/cm. For $2x10^{19}$ cm^{-3} doped quantum wells, the exchange interaction is the dominant contribution explaining the 120 meV blue-shift and a good agreement with measurements is also obtained.

2:45 PM Y4.6
III-Nitride Photonic Crystals for Blue and UV Emitters.
Tom N Oder, Jagat Shakya, Jingyu Lin and Hongxing Jiang; Physics, Kansas State University, Manhattan, Kansas.

Photonic crystals (PCs) have attracted much interest as a means of enhancing light extraction efficiency in light emitting diodes (LEDs). A majority of the reports on enhancement in light extraction using PCs have been on wavelength regions exceeding 700 nm and employing relatively large lattice periodicity in the PCs. Blue and ultraviolet (UV) LEDs based on III-nitride semiconductors are crucial for many applications but presently have very low quantum efficiency particularly for UV LEDs. The need for the improvement of extraction efficiency in these LEDs is exceptionally great. We report the achievement in nanofabrication and characterization of triangular lattice array of PCs with diameter/periodicity as small as 100/180 nm on InGaN/GaN multiple quantum well using electron beam lithography and inductively-coupled-plasma dry etching. Optical measurements on the PCs performed using near-field scanning optical microscopy showed a 60 degree periodic variation with the angle between the propagation direction of emission light and the PCs lattice. Under optical pumping, a maximum enhancement factor of 20 was obtained for emission light intensity at wavelength as short as 475 nm at room temperature with emission light parallel to the Γ-K direction of the PCs lattice. The PCs array was subsequently fabricated on blue and UV nitride LEDs of wavelength 460 nm and 340 nm respectively, and electrically characterized. Light intensity was measured from the top surface of unpackaged LED chips under current injection using charge coupled device (CCD) camera and enhancement factor of 90% - 150% was observed. Implications of our results to nitride-based optical devices, particularly for further improving LED efficiency both for blue/green as well as UV emitters are discussed.

3:30 PM *Y4.7
Structural and Optical Properties of GaN Quantum Dots.
Bruno Daudin, Noelle Gogneau, Christoph Adelmann, Eirini Sarigiannidou, Eva Monroy, Frederic Fossard and Jean-Luc Rouviere; DRFMC, cea-grenoble, Grenoble, France.

One peculiarity of GaN/AlN heterostructures is the possibility to control their morphology by varying the metal/nitrogen ratio value. As the growth mode is directly related with the strain relaxation mechanism of nitride heterostructures, a simple tuning of growth parameters enables to grow either quantum wells (QWs) or quantum dots (QDs), depending on the desired application. The Stranski-Krastanow (SK) growth mode is observed when depositing GaN on AlN in N-rich conditions. AFM, photoluminescence, and TEM characterization of dots grown according to this growth mode will be presented. The modified Stranski-Krastanow growth mode takes advantage of the self-surfactant effect of Ga observed when growing GaN in very Ga-rich conditions. Then, formation of a Ga bilayer on the growing GaN surface leads to promote FVdM growth mode while inhibiting SK mode. However, interrupting growth under

vacuum leads to desorption of the Ga film, followed by a re arrangement of the unstable 2D layer into 3D islands. A special emphasis will be put on the growth of GaN QDs with a N polarity,which have been grown on N-polar AlN deposited on C-polar (000-1)SiC. The compressive strain experienced by GaN and, consequently, the stored elastic energy is expected to be exactly the same as in Ga-polar geometry. By contrast both kinetics and surface energy are a priori different, offering the possibility to investigate further the role of such parameters in the 2D/3D transition. Both size and density of GaN islands have been compared, depending on the growth mode, i.e. SK or modified SK and depending on polarity i.e. Ga or N. The results suggest that the adatom diffusion length is a key parameter governing the formation of GaN QDs. Accordingly, it will be shown that QDs density can be controlled in the 10^{10}- 10^{11}cm ^{2}range, depending on the growth/surface diffusion conditions.

4:00 PM Y4.8

Optimization of GaN/AlGaN Quantum Wells for Ultraviolet Emitters. Andreas Hangleiter, Marco Greve, Daniel Fuhrmann and Uwe Rossow; Institute of Technical Physics, Technical University of Braunschweig, Braunschweig, Germany.

Light emission by GaInN-based heterostructures operating in the green, blue, and violet spectral region is known to be surprisingly efficient, while so far shorter wavelength GaN- or AlGaN-based structures suffer from low quantum efficiency due to nonradiative recombination at defects. We have grown GaN/AlGaN quantum well structures on sapphire substrates using low-pressure MOVPE. After a low-temperature nucleation layer a 1 micron thick AlGaN buffer layer (about 25 % Al) was grown, followed by a single or multiple GaN quantum well and an AlGaN cap layer. The emission wavelength of the QW's was varied in the 320-360 nm range by adjusting the QW width. From the data we estimate the polarization field to about 1 MV/cm. Using temperature-dependent resonant-excitation photoluminescence measurements we have determined the internal quantum efficiency (IQE) and analyzed its temperature dependence and compared the results to GaInN/GaN QW's. For the GaN/AlGaN QW's we achieve a reasonable IQE of in excess of 5 % only at fairly high excitation power, while GaInN/GaN QW's provide IQE's of up to 46 % at rather low power density, indicating a much stronger role of defects for the former. While thermal activation energies are dominated by intrinsic mechanisms for GaInN/GaN QW's, low activation barriers evident from the GaN/AlGaN data also hint at a more import role of defects.

4:15 PM Y4.9

InN Nanostructures: Strain and Morphology. Claire Pinquier[1], Francois Demangeot[1], Jean Frandon[1], Michel Caumont[1], Olivier Briot[2], Benedicte Maleyre[2], Sandra Clur-Ruffenach[2] and Bernard Gil[2]; [1]Laboratoire de Physique des Solides UMR 5477, Universite Paul Sabatier IRSAMC CNRS, Toulouse, France; [2]Groupe Etudes Semiconducteurs UMR 5650, Universite Montpellier II CNRS, Montpellier, France.

We present an experimental work of wurtzite InN nanostructures grown on a GaN layer deposited on sapphire (0001) by Metal Organic Vapor Phase Epitaxy. InN quantum dots of controlled sizes have been fabricated by using specific growth conditions and taking advantage of self-organization that results from the three dimensional Stranski-Krastanov growth mode (formation of dislocated islands on the surface). The latter takes place after a transition from a 2D growth mode as a result of strain relaxation in the film, promoted by the lattice mismatch (10%) between InN and GaN. For large InN dots, material quality assessment has been achieved by X-Ray diffraction. Then dots of nanometric size as small as 25 nm in diameter have been fabricated, together with 2D layers. Islands larger than 300 nm have been characterized by using both atomic force microscopy (AFM) and micro-Raman spectroscopy. AFM measurements revealed that the current shape of the dots correspond to truncated hexagons with a top surface diameter over base surface diameter (d) ratio of the order of 0.5. The ratio between the dot height (h) and d range from 0.07 to 0.4, which corresponds to rather flat nanostructures. The in-plane residual strain field have been evaluated by measuring the E2 phonon frequency shift in the micro-Raman spectra recorded from place to place across the dots. Careful analysis of these date makes clear that the dot aspect (e.g. the h/d ratio) is not a key parameter in determining the strain magnitude inside but rather the height of the dot, at least for the dots of diameter higher than 0.3 μm. This is not surprising keeping in mind that the dot shape is invariant as a function the size, revealing a final stage of island formation. Nevertheless, the dislocation density is believed to decrease as function of the dot thickness in the z direction, leading to various degrees of relaxation of the strain, as probed by the micro-Raman investigation. This conclusion is also reinforced by the increased strain measured in the facets of the dots in respect with its value in the dot centre. Finally, we gave evidence for the strain increase by capping the dots with a thin GaN top surface layer deposited at a rather low temperature, for preventing the thermal degradation of the underlying InN islands.

4:30 PM Y4.10

Lateral Photocurrent Spectroscopy and Photoluminescence Investigation of the Effects of Disorder on the Excitonic Transitions in AlGaN/GaN Quantum Wells. Ian Friel[1], Christos Thomidis[2], Yuri Fedyunin[2] and Theodore D Moustakas[2]; [1]Physics, Boston University, Boston, Massachusetts; [2]Elecrical and Computer Engineering, Boston University, Boston, Massachusetts.

We report on the use of lateral photocurrent (LPC) spectroscopy as a simple and sensitive method to investigate the excitonic transitions in III-nitride quantum wells. The technique is demonstrated on a 15 period $Al_{0.2}Ga_{0.8}N$/GaN multiple quantum well (MQW) structure grown homoepitaxially by plasma-assisted molecular beam epitaxy on a 4 μm thick (0001) HVPE GaN template. The LPC spectra were taken from 9 to 300 K and compared with photoluminescence (PL) spectra taken over the same temperature range. The nominally undoped MQW structure was grown in the group-III rich regime without growth interruption. The well and barrier widths were estimated from X-ray diffraction measurements to be 4 and 16 monolayers (MLs) thick respectively. Rudimentary ohmic contacts for the LPC measurements were formed by depositing In into two deeply scribed lines, resulting in electrical contact to both the MQWs and the bulk GaN template. An external electric field of only 3 V/cm is used to collect the photocurrent, which ensures that the electronic properties of the system are essentially unperturbed. Strong excitonic absorption peaks were observed in the LPC measurements up to room temperature in both the bulk GaN layer and the MQW structure, indicating that the material is of good quality. We find that the PL peak in the MQWs is Stokes-shifted with respect to the LPC peak, which we attribute to recombination of excitons from disorder-induced excitonic band-tail states in the MQWs, resulting primarily from well/barrier interface roughness fluctuations. The temperature dependence of the Stokes shift indicates that above 100 K the excitons involved in the PL are in thermal equilibrium with the lattice prior to recombining. At low temperature the data suggests a non-thermal exciton distribution, which we attribute to exciton trapping in local potential minima. An analysis of the PL integrated intensity versus temperature reveals that the exciton localization energy in the MQWs is 33 $\pm$ 6 meV. Theoretical modeling shows that this corresponds to fluctuations in the well width of 0.7 $\pm$ 0.2 ML. The magnitude of the LPC peak due to the excitonic transitions in the MQWs exhibits a non-monotonic variation with temperature, and below approximately 30 K the excitonic peak is not discernable. We develop an empirical model to explain this behavior based on the temperature variation of the low-field mechanisms of exciton dissociation and free carrier mobility.

4:45 PM Y4.11

Optical and Nano-Structures of InGaN Films with Average Indium Contents Higher Than 30%. Shih-Wei Feng[1], En-Chiang Lin[2], Tsung-Yi Tang[1], Yung-Chen Cheng[1], Hsiang-Chen Wang[1], C. C. Yang[1,2], Kung-Jen Ma[3], Ching-Hsing Shen[4], L. C. Chen[4], K. H. Kim[5], J. Y. Lin[5] and H. X. Jiang[5]; [1]Inst. Electro-Optical Eng., National Taiwan University, Taipei, Taiwan; [2]Inst. Electronics Eng., National Taiwan University, Taipei, Taiwan; [3]Department of Mechanical Eng., Chung Hua University, Hsinchu, Taiwan; [4]Center for Condensed Matter Sciences, National Taiwan University, Taipei, Taiwan; [5]Dept. of Physics, Kansas State University, Manhattan, Kansas.

Because of the large lattice mismatch between InN and GaN, leading to the low miscibility between them, indium aggregation and phase separation usually occur in InGaN through the process of spinodal decomposition. Such a process results in indium composition fluctuation and the formation of InGaN or InN clusters of quantum dot nature. With such clusters, carriers are localized in potential minima for effective radiative recombination. Typically, the process of aggregation and hence the effect of carrier localization become stronger with increasing average indium content. In this paper, we compared the optical and material properties of two MOCVD-grown InGaN thin films with average indium contents about 30 % and 40 %, respectively, between the as-grown and post-growth thermally annealed conditions. In the as-grown condition, the 30 (40) % sample emits yellow (red) photoluminescence (PL). The major part of PL spectrum of the 30 % sample was shifted from the original yellow band into the blue range upon thermal annealing. Cathodo-luminescence spectra of this sample showed that the spectral shift occurred essentially in a shallow layer of the InGaN film. The deeper layer in the as-grown sample contributed blue emission because it had been thermally annealed during the growth of the shallow layer. The spectral change was attributed to the reduction of cluster size and possibly the relaxation of quantum-confined Stark effect upon thermal annealing. The attribution was supported by the observations in the CL, x-ray diffraction and high-resolution

transmission electron microscopy results. In the 40 % sample, upon thermal annealing the red spectrum was broadened to cover almost the visit range such that it appears white in emission. Although basically spinodal decomposition also occurs, the nano-structure variation of this sample upon thermal annealing is much more complicated

SESSION Y5: Poster Session
Tuesday Evening, December 2, 2003
8:00 PM
Exhibition Hall D (Hynes)

Y5.1
Structural and Electrical Characterization of Defects in GaN after Erbium and Europium implantation. Mohammed Mamor[1], Andre Vantomme[1] and Pierre Ruterana[2]; [1]Physics Department (IKS), University of Leuven (KULeuven), Heverlee (Leuven), Belgium; [2]Laboratoire d Etudes et de Recherches sur les Materiaux, CNRS-ISMRA, Caen, France.

Recently rare earth (RE) doped semiconductors have been of considerable interest for potential applications in optoelectronics. Electroluminescence devices based on Er doped Si and GaAs were reported, however their efficiency was too low for practical application. Therefore doping RE ions into wide band gap semiconductors such as GaN is a promising approach to overcome the thermal quenching of RE photoluminescence. This combination of RE as dopant atoms incorporated into GaN results in room temperature emission of visible light in the red (Eu), green (Er) as well as bleu (Tm). As with other semiconductors, ion implantation is a crucial technique for doping GaN. This technique is very suitable for selectively introducing impurity atoms, with a precise control of the concentration and depth profile. However, due to the nuclear collisions occurring during ion implantation, defects are created during the process. We have used electrical measurements (DLTS) complemented by high-resolution x-ray diffraction, Rutherford backscattering spectroscopy and transmission electron microscopy measurements for assessment of the defects introduced in GaN during 80 keV erbium and europium ion implantation. We have used a variety of fluences, implantation temperatures as well as geometries (random and channelled implantation). Microstructural analysis shows that the two ion implantation geometries exhibit a similar defects but with a significantly lower concentration in the case of channelled implantation, revealed by Rutherford backscattering and channeling spectrometry. The damage induced by RE implantation produces a perpendicular expansion of the GaN lattice, as evidenced by high resolution X-ray diffraction. From DLTS, two prominent defects with energy levels below the conduction band were introduced during Eu implantation. Moreover, one additional electron trap, Eu1 (Ec - 0.36 eV) thusfar not observed after implantation was introduced after europium implantation. This defect is clearly seen in the random layer, but extremely weak in the channeled implanted specimen and is believed to be europium related defect. Results of the defect evolution after implantation and after annealing will be compared as well.

Y5.2
Electron Micro-Probe Analysis and cathodoluminescence spectroscopy of rare earth - implanted GaN.
Stephane Dalmasso[1], Rob William Martin[1], Paul Roger Edwards[1], Vintcheslav Katchkanov[1], Kevin Peter O'Donnell[1], Katharina Lorenz[2], Eduardo Alves[2], Ulrich Wahl[2], Bert Pipeleers[3], Vasco Matias[3], Andre Vantomme[3], Yasuo Nakanishi[4], Akira Yoshida[4] and RENiBel Network[1]; [1]Physics, University of Strathclyde, Glasgow, United Kingdom; [2]Fisica, Instituto Tecnologico e Nuclear, Sacavem, Portugal; [3]Katholieke Universiteit Leuven, Leuven, Belgium; [4]Electrical and Electronic Engineering, Toyohashi University of Technology, Toyohashi, Japan.

GaN films doped with rare-earth (RE) elements have attracted considerable attention due to the unique optical luminescent properties of intra 4f(n)-shell electron transitions which lead to sharp blue(Tm), green(Er) and red(Eu) emissions . The RENiBEl (Rare Earth doped Nitrides for high Brightness Electroluminescent devices) European research training network reports measurements obtained on RE-implanted GaN grown by MOCVD on sapphire substrates. A wide range of implantation conditions, for example variations in fluences, energies and temperatures has been used for the different ions implantations. Experiments are performed using an electron probe micro-analyser modified to allow cathodoluminescence (CL) spectral mapping. Photoluminescence spectroscopy of the same sample set allows us to compare two different mechanisms of excitation. We correlate elemental microanalysis data obtained by wavelength dispersive X-ray analysis (WDX) with simultaneously collected room temperature CL spectra. WDX allows the quantification of the RE elemental concentrations in GaN down to $\sim$ 1 % by weight in layers less than 100 nm deep. Furthermore, by varying the incident electron beam energy, details concerning the depth profile of RE can be determined. The effects of both implantation conditions and rapid thermal annealing at high temperature on the depth profile and on the luminescence properties are reported. CL measurements performed on annealed samples reveal the sharp visible emission lines and the near IR lines due to RE^{3+} intra-4f(n) atomic shell transitions.

Y5.3
Density functional calculations of the electronic properties of rare earth impurities in GaN, GaAs and AlN. Jean-Sebastien Filhol[1], Robert Jones[1], Ben Hourahine[2], Coutinho Jose[1], Patrick Briddon[3] and Mike Shaw[3]; [1]School of Physics, Exeter University, Exeter, United Kingdom; [2]Theoretische Physik, Universitat Paderborn, Paderborn, Germany; [3]School of Natural Sciences, University of Newcastle upon Tyne, Newcastle upon Tyne, United Kingdom.

Recently, rare-earth (R.E.) dopants in semiconductors have attracted great attention because of their intense photoluminescence and electroluminescence which operates to room temperatures and above. Not only can Er doped materials display infra-red luminescence close to the minimum loss wavelength region of silica-based optical fibers, but also green visible emission. Eu and Tm can emit respectively red and blue light that is of technological interest. However, there are uncertainties about the defects responsible for the luminescence. We report here density functional calculations of the structure and, for the first time, electrical properties of rare earth impurities in GaN, GaAs and AlN. We find that these defects favor metallic substitutional sites and interaction with close-by oxygen impurities, although not so strong as in Si, can be important as in GaAs. We find that concentrations of RE impurities around 1% cause only minor changes to the band structure of the host, which remains semiconducting but strongly contrasts with the rare-earth nitride bulk materials which are metallic or semi-metallic. Oxygen however, causes major changes to the electronic spectrum.

Y5.4
High temperature implantation of Tm into GaN.
Katharina Lorenz[1], S. Dalmasso[2], U. Wahl[1], E. Alves[1], R. W. Martin[2] and K. P. O'Donnell[2]; [1]Dep. Fisica, Instituto Tecnologico e Nuclear, Sacavem, Portugal; [2]Dep. of Physics, University of Strathclyde, Glasgow, United Kingdom.

Thulium ions were implanted into MOCVD grown GaN films with a fluence of $5 \cdot 10^{15}$at/cm^2 at temperatures between 20 and 500°C. The lattice damage introduced by the implantation and the effect of post-implant annealing were investigated with Rutherford backscattering spectrometry in the channeling mode (RBS/C). Whereas for RT implantation the implanted layer has become completely amorphous, high temperature implantation has inhibited amorphisation. For temperatures higher than 300°C the RBS/C results clearly show two different damage regions - one at the surface and the second deeper in the crystal coinciding with the Tm depth profile. The intensity of the surface damage peak as well as that of the deeper damage region decrease with increasing implantation temperature. For temperatures above 300°C the Tm profile as well as the damage peak reach deeper into the crystal. This can be coursed either by a diffusion of defects and implanted species during the implantation and the dynamic annealing process or by an enhanced channeling effect due to the suppression of amorphisation. For the samples that were not completely amorphous a large part of the Tm atoms were found to be incorporated in Ga-sites. The optical properties of the ion implanted GaN films have been studied by room temperature cathodoluminescence measurements. Directly following the implantation no Tm-related luminescence was observed. Subsequent annealing of the samples achieved optical activation, revealing well-defined emission due to intra-4f-shell transitions of the Tm^{3+} ions in the blue spectral range at 477 nm and in the near infra-red at 804 nm.

Y5.5
Processing of rare earth doped GaN with ion beams.
Katharina Lorenz[1], U. Wahl[1], E. Alves[1], B. Pipeleers[2], V. Matias[2], A. Vantomme[2], S. Dalmasso[3], R. W. Martin[3], K. P. O'Donnell[3], N. Rousseau[4], G. Halambalakis[4], S. Ruffenach[4], O. Briot[4], T. Wojtowicz[5] and P. Ruterana[5]; [1]Dep. Fisica, Instituto Tecnologico e Nuclear, Sacavem, Portugal; [2]Instituut voor Kern- en Stralingsfysica, KULeuven, Leuven, Belgium; [3]Dep. of Physics, University of Strathclyde, Glasgow, United Kingdom; [4]GES, Universite de Montpellier II, Montpellier, France; [5]LERMAT, ENSICAEN, Caen, France.

Doping of GaN with rare earth elements (RE) allows the production of electroluminescent emitters that cover the entire visible wavelength range. This opens the possibility to develop integrated, all-nitride light-emitting devices for several applications in display technology. In this work we study structural and optical properties of GaN doped

with RE by ion implantation and compare them to results obtained for GaN doped during MBE growth. GaN epilayers grown by MOCVD were implanted with Er, Tm and Eu with different energies, doses and fluxes and at different implantation temperatures in order to find the optimum implantation conditions. The recovery of the implantation damage was studied using both rapid thermal annealing (RTA) and furnace annealing with elevated nitrogen pressure. Rutherford backscattering spectrometry in the channeling mode was used to monitor the evolution of damage introduction and recovery in the Ga sublattice and to establish the lattice site location of the RE. The nature of structural defects was studied with TEM. The optical properties of the samples were analysed by room temperature cathodoluminescence. For optical activation of the implanted samples annealing was necessary. We observe RE related emissions in the green, red and blue for Er, Eu and Tm, respectively, and in the infrared for Er and Tm.

Y5.6

Microstructure and Photoluminescence Investigations of Er doped GaN layers grown by MBE. Tomasz Wojtowicz[1], Alain Braud[3], Hock M. Ng[2], Jean L. Doualan[3] and Pierre Ruterana[1]; [1]LERMAT FRE 2149, CNRS-ENSICAEN, Caen, Normandy, France; [2]Lucent Technologies, Murray Hill, New Jersey; [3]CIRIL UMR, CNRS-ENSICAEN, Caen, Normandy, France.

For a few years now, it has been possible to dope GaN layers using MBE growth. This aims to use the wide band gap semiconductors as hosts to the rare earth and exploit the sharp emission lines from intra 4f shell transitions. It was shown that the whole visible spectrum can be covered by changing the rare earth or exciting different levels. It is also suspected that like in some systems for instance Si(nano)/SiO2, the energy coupling could involve defects. In this work, we carry out TEM and HREM analysis on GaN layers grown on sapphire and doped in situ. Investigations are carried out in parallel using photoluminescence and photoluminescence excitation experiments in order to determine the mechanisms that govern the energy transfer between the rare earth ion and the host GaN. It has been shown previously that the emission peaks at Er concentrations of about 1% and that it dramatically decreases with Er concentration probably because of compositional quenching. We therefore study the evolution of the microstructure versus composition and try to explain the quenching effects that can be related to the microstructure. Moreover, it has also been suggested that Er emission in GaN could be related to energy transfer through the mediation of defects. We analyse the atomic structure of the crystallographic defects that are present inside the layers and try to correlate it with the incorporated rare earth atoms.

Y5.7

Luminescence Properties of Eu ion-implanted GaN. Shin-ichiro Uekusa and Isao Tanaka; Department of Electrical and Electronic Engineering, Meiji University, Kawasaki, Kanagawa, Japan.

Since Group-III nitrides light device has high luminosity, it is expected as a new white light source replaced with a fluorescent light. Gallium nitride (GaN) is very useful host material because it equips a wide band gap and improve the luminescence properties of rare earth ions. Especially Eu ion shows luminescence of about 600nm by the transition from the $^5D_0$ to ^7F_J (J=0~4), it is expected as a element which bears red light emission in RGB colors. But, luminescence from rare earth ion occurs thermal quenching. Therefore, luminescence is weak and difficult to use at room temperature as a white light source. The wafer used in this work was a Si-doped ($n=9.8\times10^{17}cm^{-3}$) epitaxial n-GaN layer grown on sapphire substrate. The Eu ion was implanted at an energy of 300keV with a dose of $1\times10^{15}cm^{-2}$ at room temperature. After the ion implantation, these samples were thermally annealed at temperatures ranging from 1000 to 1400°C and at times ranging from 10 to 60 minutes by rapid thermal annealing. The heating and cooling rates were 5°C/s. Before annealing, the apparatus was pumped down to a base pressure of 5.0×10^{-6} Torr before an atmosphere gas was fed into the vacuum chamber. The gas used to this experiment was Ar gas at 1 atm. Photoluminescence (PL) spectra and its lifetime were measured at temperatures ranging from 15K to 300K using the 325.0nm line of a He-Cd laser with a power of 10mW. Signals were dispersed by a 1m-focal-distance double-grating monochromator and then detected by a GaAs photomultiplier. Optimal annealing condition was 1300°C, 30 minutes for Eu-related luminescence intensity and PL was observed at room temperature. Lifetime was 4.6 msec at 15K and became short as temperature rose. We calculated activation energy (E_a=8.5eV) and studied on thermal quenching process. Its quenching dominated in the low temperature range from 15K to 140K, we found the nonradiative recombination in the transition from the $^5D_0$ to $^7F_2$ of Eu. We report systematically on the obtained results.

Y5.8

Luminescent Holmium Doped Amorphous AlN Thin Films Deposited in Planar and Cylindrical Geometries for Waveguides and Laser Cavities. Muhammad Maqbool, Hugh H Richardson, P. Greg van Patten and Martin E Kordesch; Physics and Astronomy, Ohio University, Athens, OH, Ohio.

Holmium doped AlN thin films have been deposited on flat silicon substrates and optical fibers of different diameters, in order to fabricate resonant cavities for lasers. In particular, the films on fiber substrates are expected to perform as cylindrical waveguides or "whispering gallery" cavities. The AlN films are deposited by reactive sputtering at liquid nitrogen temperature, using 100 - 200 Watts RF power, 5-8 mTorr nitrogen, using a metal target of Al and Ho. The aim is to obtain lasing in rare earth doped (< 1 at. %) amorphous nitride semiconductors. One micron thick films of AlN:Ho have been deposited on flat silicon substrates and 2 micron thick films on 80 micron and smaller optical fibers. X-ray Diffraction and SEM studies show that films deposited on flat silicon are amorphous while the ones deposited on the fibers show columnar growth and some gain structure, most probably due to a temperature rise at the substrate during deposition. Cathodoluminescence (CL) emission is observed in thermally activated AlN:Ho in both crystalline and amorphous forms. An intense, narrow emission peak is observed at 547 nm. Small peaks are also observed at 490 nm, 661 nm and 759 nm. The most promising wavelength for our design is laser emission from the 5S2 to 5I8 transition at 547nm; although a dozen laser transitions have been observed in Ho ions. Methods to pump the cavities both optically and using electrons, methods to ensure efficient excitation of the Ho ions and efforts to construct cylindrical waveguides from the amorphous films will be presented.

Y5.9

Lattice Location of Er in GaN CO-Implanted With O and C. Bart De Vries[2], Ulrich Wahl[1], Elisabete Rita[1], Armandina L. Lopes[3], Eduardo Alves[1], Guilherme Correia[1,4], Vasco Matias[2], Andre Vantomme[2] and collaboration The ISOLDE[4]; [1]Fisica, Instituto Tecnologico e Nuclear, Sacavem, Portugal; [2]Instituut voor Kern-Stralingsfysica, Katholieke Universiteit Leuven, Leuven, Belgium; [3]Fisica, Universidade do Aveiro, Aveiro, Portugal; [4]CERN, Geneva, Switzerland.

Rare earth doped GaN is a promising material with regards to the realization of 3-color integrated optical devices such as displays. It has been reported that co-doping with O or C enhances the luminescence of Er-doped GaN [1, 2]. A possible mechanism that has been suggested in that respect is that these co-dopants may promote the incorporation of Er on substitutional Ga sites. However, the role of co-dopants is currently under discussion and there exist conflicting views whether co-doping is beneficial at all in the case of Er-implanted GaN samples [3]. We report here on emission channeling lattice location studies of ^{167m}Er in pure GaN, GaN co-implanted with O and GaN co-implanted with C. The emission channeling technique is based on the fact that charged particles emitted by radioactive probe atoms in a single crystal experience channeling or blocking effects along the major crystal axes and planes. The resulting anisotropic emission yield depends characteristically on the lattice site occupied by the probe atoms. One of the GaN samples was pre-implanted with ^{16}O at 11 keV using a fluence of 5×10^{14} cm^{-2}, a second sample with 5×10^{14} cm^{-2} of ^{12}C at 8 keV. The implantation energies were chosen so as to optimize the overlap with the Er atoms. Afterwards radioactive ^{167}Tm ($t_{1/2}$=9.25 d) was implanted at 60 keV to a dose of 2×10^{13} cm^{-2} into all three samples. The isotope ^{167}Tm decays to the isomeric state ^{167m}Er ($t_{1/2}$=2.28 s) of erbium. The conversion electrons emitted in the subsequent decay to the ground state were measured around the [0001], [-1102], [-1101] and [-2113] directions by means of a two-dimensional position-sensitive detector. Already in the as-implanted state the majority (~75%) of ^{167m}Er was found on substitutional Ga sites in all three samples. The remainder was located on random sites. The root mean square (rms) displacements from the perfect substitutional Ga site were of the order of 0.14 Å in the pure GaN sample, and 0.15 Å in the co-doped samples. This is larger than the thermal vibration amplitude of Ga in GaN (0.07 Å), which suggests the Er atoms are slightly displaced or have point defects in their vicinity. Annealing up to 900°C did not significantly improve the substitutional fractions, but decreased the rms displacements down to about 0.11 Å in the pure GaN sample, and to 0.12 Å in the two co-doped samples. The differences between the three samples are well within the experimental error bars and the Er in the co-implanted samples thus exhibited the same behavior as the Er in virgin GaN. Our findings therefore show that co-implanting of Er with O or C into GaN does not significantly affect the incorporation of Er into Ga sites in the case of low-dose ion implantation. [1] J.T. Torvik et al, J. Appl. Phys. 81 (1997) 6343. [2] M. Overberg et al, Mater. Sci. Eng. B 81 (2001) 121. [3] E. Alves et al, Mater. Sci. Eng. B 81 (2001) 132.

Y5.10

Lattice location of Tm, Er and Eu ions in GaN host studied

by X-ray Absorption Fine Structure(EXAFS).
Vintcheslav Katchkanov[1], Frederic Mosselmans[2], Kevin Peter O'Donnell[1], Stephane Dalmasso[1], Robert Martin[1], Y Nakanishi[3], A Wakahara[3], A Yoshida[3] and RENiBEL Network[4]; [1]Department of Physics, Strathclyde University, Glasgow, Scotland, United Kingdom; [2]Synchrotron Radiation Department, CCLRC Daresbury Laboratory, Warrington, United Kingdom; [3]Toyohashi University of Technology, Toyohashi, Japan; [4]RENiBEL Network, European Union.

GaN doped with rare-earth (RE) ions is a promising material for light emitting devices in the visible spectral region [1, 2]. The efficiency of RE ion emission depends crucially on their distribution over the available lattice and interstitial sites and on the symmetry of the local environment, through the relaxation of selection rules for intra-4f shell transitions [3, 4]. EXAFS measurements can be used to obtain information about local structure in the neighbourhood of an atom targeted by its characteristic X-ray absorption [5]. The main advantages of EXAFS as a structure- determining technique are: it is element specific so can provide information on the local structure around an element which is present in trace concentrations, it is completely non-destructive. Lattice location of RE ions, Eu, Er and Tm, implanted or doped in-situ in GaN films has been studied by means of EXAFS measurements at the Daresbury synchrotron. It has been revealed that the most favourable site for RE ions is substitutional Ga site in GaN matrix. [1] A. J. Steckl et.al., Materials Science and Engineering B 81, p 97 (2001) [2] M.J. Garter and A.J. Steckl, IEEE Transactions on Electron Devices 49, p 48 (2002) [3] S. Kim et.al., Materials Science and Engineering B 81, 136 (2001) [4] J. M. Zavada et.al., Materials Science and Engineering 81, p 127 (2001) [5] D. Wruck et. al., Seniconductor Science and Technology 16, p L77 (2001)

Y5.11
Enhancement of magnetic properties by co-implantation of Mn and N ions to p-type GaN. Jeong Min Baik[1], Yoon Shon[2], Tae Won Kang[2] and Jong-Lam Lee[1]; [1]Materals Science & Engineering, POSTECH, Pohang, Kyungbook, South Korea; [2]Quantum Functional Semiconductor Research Center, Dongguk University, Seoul, South Korea.

A Mn doped GaN has become one of the most important spintronic materials because its Curie temperature is higher than room temperature according to the theoretical calculation of Dietl et al. Recently, room temperature ferromagnetism has been observed in Mn doped GaN. However, it was difficult to obtain a heavy doping of Mn in GaN because of the low solubility limit of Mn in GaN. In this paper, we proposed a new method for the enhancement of the Mn solubility in GaN using co-implantation of N and Mn ions into GaN. An undoped GaN layer with a thickness of 1μm was grown, followed by a growth of 1-μm-thick p-type GaN doped with Mg. Net hole concentration in the film was determined to be 2.5×10^{17} cm^{-3} by Hall measurements. First, the N^+ ions were implanted at energy of 35 KeV to position the ion peak 80 nm from the surface. The Mn^+ ions were then implanted at energy of 180 KeV to place its peak range at the same position as that for the N implanted samples. The N and Mn implant dosages were 5×10^{16} cm^{-2}. Subsequent annealing at 800 °C for 30,s was performed under flowing N_2 gas in a face-to-face condition. For reference, Mn-implanted GaN samples were also prepared. The magnetization data showed that the curie temperature of co-implanted sample was above 300 K. From EXAFS spectra, it was observed that the majority of implanted Mn ions substituted for the Ga sites in GaN. On the other hand, Mn nitrides such as $Mn_6N_{2.58}$ and Mn_3N_2 were formed and the Curie temperature was low (< 100 K) in the Mn-implanted samples. These results confirm that the ferromagnetism in Mn-doped GaN is derived entirely from the substitution of Mn^{2+} ions for Ga sites.

Y5.12
Local structure study of highly Mn doped GaN by fluorescence X-ray absorption. Gema Martinez-Criado[1], Andrea Somogyi[1], Martin Eickhoff[2] and Martin Stutzmann[2]; [1]ID22: Micro-Fluorescence/Imaging/Diffraction Group, European Synchrotron Radiation Facility (ESRF), Grenoble, France; [2]Walter Schottky Institute, Technical University of Munich, Garching, Munich, Germany.

The atomic configuration and charge states of Mn in GaN were studied by means of extended X-ray absorption fine structure (EXAFS) and X-ray absorption near-edge structure (XANES) analyses on the micrometer scale. In fluorescence detection mode, the spectra were taken from molecular-beam-epitaxy grown GaN:Mn layers deposited on (0001) sapphire substrates with high Mn concentrations, ranging from 1018 up to 1021 cm-3. In addition to the GaN p-type doping, Mn impurities introduce special magnetic properties, leading to ferromagnetism with an extremely high Curie temperature above 740 K. The systematic behaviour of the bond length distortion as Mn content increases in the GaN lattice is reported. The local structure and bonding configurations around the Ga in these films have been analyzed as well. In summary, the obtained local structure information has provided direct evidence that the magnetic Mn impurities can indeed substitute for the Ga host atoms even in highly concentrated samples.

Y5.13
An Optical Spectroscopic Method to Monitor the Formation of Metallic Secondary Phases in Diluted Magnetic Semiconductors. Sung Seok Ambrotius Seo[1], T. W. Noh[1], Y. D. Park[2], G. T. Thaler[3], M. E. Overberg[3], C. R. Abernathy[3], S. J. Pearton[3], H. C. Jeon[4] and T. W. Kang[4]; [1]ReCOE & School of Physics, Seoul National University, Seoul, South Korea; [2]CSCMR & School of Physics, Seoul National University, Seoul, South Korea; [3]Department of Materials Science & Engineering, University of Florida, Gainesville, Florida; [4]Quantum Functional Semiconductor Research Center, Dongguk University, Seoul, South Korea.

Recently, III-V based diluted magnetic semiconductors (DMS) have attracted a lot of attention due to their potential spintronic applications. In spite of development of elaborate growth techniques, it is still difficult to avoid formation of secondary phases due to the solubility limit. Especially, formation of some inter-metallic compounds, such as MnAs, Mn_xN_y, and GaMn, should be carefully monitored, since they are known to be ferromagnetic with high ferromagnetic Curie temperatures. So far, standard X-ray diffraction and transmission electron microscopy measurements have been widely used, but the possible formation of the secondary phases and their roles in the observed ferromagnetic properties remain to be controversial. Therefore, it is highly desirable to develop noble experimental techniques to check the formation of the secondary phases. We found that optical spectroscopy techniques can provide a nondestructive method to monitor the formation of such metallic secondary phases by observing a resonant absorption, called /sphere resonance/, in transmission spectra. For example, we will show spectroscopic evidence on the formation of Mn_4N inter-metallic particles in GaN:Mn, by observing the 1.2 eV resonant absorption and comparing its temperature dependence with predictions of the Maxwell-Garnett theory. Moreover, our spectroscopic techniques can provide some quantitative information, such as the volume fraction of Mn_4N inter-metallic particles [1]. In this presentation, we will show how the optical spectroscopic techniques allow us to check the formation of the metallic secondary phases in various DMS samples, such as GaN:Mn, GaAs:Mn, and InAs:Mn. The spectroscopic signature of possible metallic secondary phases in each DMS and analysis method will be also discussed. References [1] Seo *et al.*, Appl. Phys. Lett., **82**, 4749 (2003)

Y5.14
Resonant Magnetopolaron Effect on Shallow Donors in GaN. Andrzej Stefan Wysmolek[1], R. Stepniewski[1], M. Potemski[2], B. Chwalisz[1], K. P. Korona[1], J. M. Baranowski[1], D. C. Look[3], S. S. Park[4] and K. Y. Lee[4]; [1]Institute of Experimental Physics, Warsaw University, Warsaw, Poland; [2]Grenoble High Magnetic Field Laboratory, Grenoble, France; [3]Semiconductor Research Center, Wright State University, Dayton, Ohio; [4]Samsung Advance Institute of Technology, Suwon, South Korea.

The interaction of longitudinal-optical (LO) phonon with highly excited shallow donor states in GaN, observed using magneto-spectroscopy of neutral donor bound excitons (D0X) in magnetic fields up to 28T, is reported. The magneto-luminescence experiments have been performed on a thick freestanding GaN. Photoluminescence spectrum of this material shows pronounced emission due to silicon and oxygen donor bound excitons. Beside the principal recombination transition of D0X in which donors are left in their ground states, two electron satellites (TES) in which donors are left in one of the excited states are observed. In particular TES connected with oxygen donor show several transitions involving different excited states are observed. Detailed magnetooptical studies allowed us to identify transitions involving the excited states with n=2 (2s, 2p0, 2p- and 2p+), as well as excitations to several higher (n > 2) donor states [1]. The intensities of TES related to the states with high n-index decrease with increasing of the magnetic field strength. However, when the high n-index states are tuned into resonance with LO-phonon replica of the principal D0X transition, their intensities are strongly enhanced. The avoided-crossing between LO-phonon and several donor states is observed. The most striking effects are observed for a series of states: 3d+1, 4f+2, 5g+3, 6h+4, 7i+5... which, in general, are characterized by l=n-1 and m=n-2 quantum numbers. The characteristic property of these states is that their wavefunctions are extended along the magnetic field direction. The obtained results are discussed in terms of electron-phonon interaction and provide information about the magnitude of the resonant interaction of LO-phonons with impurity-bound electrons in GaN. [1] A. Wysmolek, K. P. Korona, R. Stepniewski, J. M. Baranowski, J. Bloniarz, M. Potemski, R. L. Jones, D. C. Look, J. Kuhl, S. S. Park, and S. K. Lee,

Y5.15
Hydrogen-related Local Vibrational Modes in GaN:Mg Grown by Molecular Beam Epitaxy. David Pastor[1], Ramon Cusco[1], Luis Artus[1], Fernando Naranjo[2] and Enrique Calleja[2]; [1]Institut Jaume Almera, C.S.I.C., Barcelona, Spain; [2]Departamento Ingenierin Electronica, ETSI Telecommunicacion, Universidad Politecnica, Madrid, Spain.

Despite the achievement of effective p-type doping of GaN using Mg as a dopant, basic understanding of p-type doping still remains an issue. It has been recognized that hydrogen plays an important role in p-type doping of GaN, strongly passivating the acceptor states of MOCVD-grown Mg-doped GaN and making post-growth annealing treatments necessary to obtain p-type conductivity. Contrary, GaN:Mg samples grown by MBE usually exhibit native p-type character in the as-grown state. We report a Raman scattering study of Local Vibrational Modes (LVMs) on Mg-doped GaN grown by MBE. The samples were Mg-doped GaN films of $\approx$1.4 μm thickness grown on Si(111) substrates at T_{Mg}=450 °C. The Raman experiments were performed using a Raman microprobe with the 514.5 nm excitation wavelength and typical spot size of $\approx$1 μm. The spectra were acquired in the x(yy)x in-plane configuration to maximize the scattering volume. In the region of the acoustic and optical modes of GaN, we clearly observed two distinct peaks at 262 and 656 cm^{-1}, which correspond to local Mg modes with A_1 symmetry. These LVM peaks, which unambiguously show the presence of Mg dopants in substitutional Ga positions, were observed in MOCVD samples only after thermal annealing. Additionally, we observed four Raman peaks in the spectral region around 2200 cm^{-1}, where LVM associated with Mg-H complexes and H-decorated nitrogen vacancies occur, suggesting that H passivation may also take place in GaN:Mg samples grown by MBE. Contrary to the case of MOCVD samples, we did not detect any Raman signal at about 3120 cm^{-1}, which indicates that for MBE growth H atoms do not bond to N to form N-H complexes. The different behavior of H in hydrogenated GaN:Mg samples grown by MBE and MOCVD correlates with the different electrical behavior that is usually exhibited by samples grown using these two techniques.

Y5.16
Non-Equilibrium Acceptor Concentration in GaN:Mg Grown by Metalorganic Chemical Vapor Deposition. Yinyan Gong[1], Y Gu[1], Igor L Kuskovsky[1], G F Neumark[1], J Li[2], J Y Lin[2] and H X Jiang[2]; [1]Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York; [2]Department of Physics, Kansas State University, Manhattan, Kansas.

GaN has been of great interest for various applications. To achieve optimal device operation, good bipolar doping is required. GaN:Mg with a hole concentration of 10^{18} cm^{-3} has been achieved (for a review, see e.g. [1]). Such good p-doping is obtained either by post growth annealing of material grown by metalorganic chemical vapor deposition (MOCVD), where such annealing removes compensating hydrogen, or via molecular beam epitaxy [1]. Both processes are expected to result in non-equilibrium dopant concentrations [2, 3]. Here, we present experimental results that prove non-equilibrium concentrations for the MOCVD case. Our samples are cut from a single wafer of GaN:Mg grown by MOCVD on sapphire and activated by rapid thermal annealing (RTA) at 950 °C for 8sec. We then further annealed several of these pieces at various temperatures in nitrogen ambient for over 12 hours. Temperature-dependent Hall-effect measurements showed that hole concentrations decreased by an order of magnitude or more in samples annealed at high temperatures (>850 °C) compared with the original RTA activated sample, while the acceptor activation energy remains the same for all pieces. This behavior is explained by Mg concentrations in excess of the equilibrium solubility limit. Thus, at high enough temperatures, Mg, in the absence of hydrogen, diffuses either to form electrically inactive precipitates or is eliminated. Furthermore, we shall show that photoluminescence results are consistent with the Hall-effect measurements.

Y5.17
Effect of Impurities on Raman and Photoluminescence Spectra of AlN Bulk Crystals. Andrei Sarua[1], Srikaran Rajasingam[1], Martin Kuball[1], Nuria Garro[2], Oscar Sancho[2], Ana Cros[2], Andres Cantarero[2], Daniel Olguin[3], Bei Liu[4], Dejin Zhuang[4] and James H. Edgar[4]; [1]Department of Physics, University of Bristol, Bristol, United Kingdom; [2]Institut de Ciencia dels Materials, Universitat de Valencia, Valencia, Spain; [3]Depto. de Fisica, Centro de Investigacion y de Estudios Avanzados del Instituto Politecnico Nacional, Mexico, Mexico; [4]Department of Chemical Engineering, Kansas State University, Manhattan, Kansas.

AlN has attracted great attention for its use as a wide bandgap high thermal conductivity substrate for electronic and opto-electronic nitride devices. However its properties are highly affected by incorporation of impurities during growth, for instance Al has a large affinity to oxygen. Raman and photoluminescence (PL) spectroscopy were applied to explore tracing of common impurities in AlN by optical means, in particular of oxygen. Bulk AlN crystals grown by the high temperature sublimation method were studied. Composition analysis of the samples was obtained by EDX, Leco combustional method and laser ablation mass spectroscopy. The levels of oxygen, carbon, silicon and magnesium impurities were derived from these analyses. Micro-Raman spectra of the bulk AlN samples were measured in different polarisations and using different excitation wavelengths. The presence of vibrational modes at 585 cm^{-1} and 930-950 cm^{-1} was detected in addition to the usual Raman modes of bulk AlN. The 585 cm^{-1} mode was attributed to an oxygen local vibrational mode (LVM) in AlN, Al-O complex. PL measurements were performed with sub-bandgap light excitations of 4.5 eV and 3.72 eV. A correlation between the observed 585 cm^{-1} mode and an oxygen related luminescence band in PL spectra at 3.3 eV was found. Theoretical calculations were applied to estimate the frequencies of LVMs in AlN and reasonable agreement to the experimental value for the oxygen LVM was achieved.

Y5.18
Surface Potential Measurements of doping and defects of p-GaN. Maria Losurdo[1], Maria Michela Giangregorio[1], Giovanni Bruno[1], April Susan Brown[2], William Alan Doolittle[3], Gon Namkoong[3] and Thomas Myers[4]; [1]PlasmaChemistry Center, IMIP-CNR, Bari, Italy; [2]Electrical and Computer Engineering, Duke University, Durham, North Carolina; [3]School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [4]Physics, West Virginia University, Morgantown, West Virginia.

Effective p-type doping in GaN is still a crucial issue for the realization of efficient optical and electronic devices. The most investigated p-dopants of Mg and Be suffer from acceptor passivation through hydrogen complexes. In this study, we use non-destructive optical and electrical probes such as spectroscopic ellipsometry and Kelvin probe force microscopy (KPFM) in conjunction with non-contact atomic force microscopy (AFM) for investigating of the interaction of Mg- and Be-dopants with atomic hydrogen and for characterizing passivation of defects, such as, dislocations, micropipes and inversion domains with atomic hydrogen. GaN epitaxial films grown by both metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) doped with both Be and Mg at a doping level in the range from 10*17cm-3 to 10*19cm-3 are exposed to an atomic hydrogen flux produced by a r.f. (13.56MHz) remote plasma source. The reactivity towards atomic hydrogen including bulk hydrogen diffusion, defect (dislocations) passivation and p-dopant deactivation is monitored in real time by spectroscopic ellipsometry that monitors variation of the GaN dielectric function upon atomic hydrogen exposure. Through the analysis of the broadening, energy-shift and amplitude of the GaN exciton transition at 3.4 eV in the ellipsometric spectra, the effect of atomic hydrogen on the p-dopant deactivation is inferred. The ellipsometry data are corroborated by surface potential variations. Surface potential measurements reveal a decrease in surface potential directly correlated with regions of deactivation of the Mg-dopant and Be-dopant by atomic hydrogen. Furthermore, spectroscopic ellipsometry monitoring of the interaction of GaN:Be and GaN:Mg films with atomic hydrogen reveals a different Mg-H and Be-H bonding. A comparative study with n-type GaN:Si is carried out in order to understand the effect of doping on the GaN surface potential. An increase in the donor density in the GaN by either n-doping or hydrogen-related deactivation of p-dopant result in reduced SKP signal because of the shift of the Fermi level toward the conduction band. The effect of surface temperature and p-dopant concentration on the Mg-H and Be-H interaction is investigated. Furthermore, direct measurements of potential variations around dislocations, micropipes and inversion domains are detected to reveal the nature of the above defect charges as well as their spatial extent and modifications by atomic hydrogen treatments.

Y5.19
Low-temperature Activation of Mg-doped p-GaN with Catalyst Layers. Hyunwook Shim, YunKyum Kim, Eun-Kyung Suh and HyungJae Lee; Department of Semiconductor Science and Technology, Chonbuk National University, Chonju, South Korea.

Mg-doped GaN layer has been used as a p-type layer in the fabrication of InGaN based light-emitting diode (LEDs) and laser diodes (LDs). Although a successful doping of p-type GaN with Mg impurity has been achieved, the following points are still not unsolved prolbelms : (1) understanding of electronic characteristics and role of various defects in Mg-doped GaN and (2) difficulties in achieving high hole concentration due to high ionization energy and suppression of Mg incorporation rate by formation of Mg related complexes and therefore

low activation rate of Mg (roughly 1 %). In this work, we show the improvement of activation rate and ohmic contact characteristics by rapid thermal annealing (RTA) using Ni and Au catalyst layers on p-GaN layer. Electrical characteristics of Mg-doped p-GaN grown on sapphire substrates by metal organic chemical vapour deposition (MOCVD) and activation by RTA using No and Au catalyst layer were investigated using Hall measurements and current-voltage (I-V) characteristics. We alos fabricated and compared between LED with normal temperature used commonly in our fabrication process (930 °C) and with lowe temperature activation using catalysts layer. The p-GaN activated with Au layer exhibited a maximum carrier concentration of 9×10^{17} cm^{-3} at 800 °C, which is lower than normal RTA temperature and improved Ohmic characteristics. It was revealed that Ni and Au layers on p-GaN enhance activation of the acceptor. This enhancement can be attributed to the catalytic effect for the hydrogen desorption and ionization energies of Mg acceptors in p-GaN layer activated with catalysts. Au shows better catalytic effect in p-GaN layer than Ni. We could improve the electrical and optical properties of InGaN/GaN blue LEDs due to improvment of ohmic characteristics by increase of Mg activation rate and reduction of degradation of InGaN/GaN quantum well by low temperature activation of Mg using catalyst layer in LED structures.

Y5.20

Formation and Dissociation of Hydrogen-related Defect Centers in Mg-doped GaN. Olaf Gelhausen[1], M. R. Phillips[1], E. M. Goldys[2], T. Paskowa[3], B. Monemar[3], M. Strassburg[4] and A. Hoffmann[4]; [1]Microstructural Analysis Unit, University of Technology, Sydney, Sydney, New South Wales, Australia; [2]Division of Information and Communication Sciences, Macquarie University, North Ryde, New South Wales, Australia; [3]Department of Physics and Measurement Technology, Linkoping University, Linkoping, Sweden; [4]Institute for Solid-State-Physics, Technical University Berlin, Berlin, Germany.

Scanning cathodoluminescence (CL) spectroscopy was used to study the electron beam-induced formation and dissociation processes of H-related defect complexes and their role in the acceptor compensation mechanisms in MOVPE-grown Mg-doped p-type GaN. In addition to the well-known shallow donor-acceptor-pair (DAP) band centred at 3.27 eV (at 4 K), a deeper DAP band centred at 3.13 eV was identified. During electron beam irradiation, the shallow DAP, consisting of a Mg_{Ga} acceptor and a shallow hydrogen-related donor, is reduced and the deeper DAP band emerges, consisting of the Mg_{Ga} acceptor and a deeper donor complex, presumably a hydrogenated nitrogen vacancy. The shallow DAP band is attributed to a DAP consisting of the Mg acceptor and a H-related donor, since its beam-induced decrease is correlated with the dissociation process of neutral Mg-H complexes. The time-dependence of the Mg-H dissociation reaction was modeled by first and second order kinetic processes. An increase of the electron beam power resulted in faster dissociation rates. The upper limit for the thermal activation energy of the shallow hydrogen-related donor was determined to be 25 meV by temperature-resolved CL measurements. The DAP-character of the deeper DAP was confirmed by its blueshift with increasing excitation density. Since the loss in CL intensity of the shallow DAP due to the dissociation of Mg-H complexes is almost completely counterbalanced by the gain in CL intensity of the deeper DAP, the deeper donor is attributed to a hydrogenated nitrogen vacancy complex, which is located ~160 meV below the conduction band edge and represents another compensation mechanism. To support this assignment, a part of the sample was thermally annealed in $H_2(5\%)/N_2$ atmosphere. The annealing process strongly reduced the CL intensity of the deeper DAP. It is suggested that in the presence of hydrogen during annealing, Mg-H complexes are formed, and, due to the upshifting of the Fermi-level towards the midgap region, the formation of other defect complexes (i.e. V_N^+) is suppressed.

Y5.21

Inversion Domain Platelets Induced by Mg-Doping in Laterally-Grown AlGaN Films. Rong Liu[1], F A Ponce[1], D Cherns[2], H Amano[3] and I Akasaki[3]; [1]Department of Physics and Astronomy, Arizona State University, Tempe, Arizona; [2]H. H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom; [3]Department of Materials Science and Engineering, Meijo University, Nagoya, Japan.

Mg is a commonly used p-type dopant in nitride semiconductors. High doping concentration is required to produce sufficient p-type conductivity. This often results in formation of Mg-rich pyramidal precipitates. In this work, we have studied the effect of doping on the microstructure of thick Al0.03Ga0.97N films deposited on groove-patterned sapphire substrates. A Mg-doping concentration of ~10E20 cm-3 is used to enhance lateral overgrowth rate. TEM observations were performed in different projections to study the doping effect on microstructure properties. Plan-view images reveal bar-shaped defects in the regions grown above the grooves. Cross-sectional images reveal that the bar-shaped defects have a platelet structure, with the plate parallel to (1-100)AlGaN plane. The platelets form faceted trenches on the sample surface. The platelet defects appear to be formed due to coalescence of neighboring lateral overgrowth domains. Lattice images exhibit a slight shift of the basal plane lattice fringes at the platelet boundary, indicating that the defects are inversion domains. The high doping level also results in formation of Mg-rich pyramidal precipitates in this film. The precipitates are denuded in the vicinity of the platelet defects, suggesting that the inversion domain platelets consume Mg impurities, and drain the impurities in the neighboring region. In short, we observe inversion domain platelets in the overgrowth region of AlGaN, and a formation mechanism is proposed by taking into consideration Mg segregation to the coalescence boundary between neighboring lateral overgrowth domains. Understanding of these defects is critical for producing homogenous p-type materials in high performance devices.

Y5.22

TEM Investigation of Defect Reduction and Etch Pit Formation in GaN. Angelika Vennemann, Jens Dennemarck, Claudia Roder, Roland Kroeger, Tim Boettcher, Detlef Hommel and Peter Ryder; Institute of Solid State Physics, University of Bremen, Bremen, Germany.

The reduction of the threading dislocation (TD) density in GaN grown by metal organic vapor phase epitaxy (MOVPE) is of major importance in order to improve electronic devices. With the investigated SiN_x micromasking the dislocation density can be reduced by more than an order of magnitude, as shown by plan view transmission electron microscopy (TEM). The reduction of TDs in GaN grown on <0001> sapphire is due to bending of the TDs into the {0001} plane, such that they form dislocation loops if they meet dislocations with opposite Burgers vectors. Accordingly, the achievable reduction of the dislocation density is limited by the probability that appropriate dislocations meet. In order to gain easier access to the dislocation structure, the GaN samples of this study were chemically wet etched with an H_2SO_4:H_3PO_4 acid for varying times. The atomic force microscopy (AFM) and TEM investigations showed different types of etch pits. After brief etching, pure edge dislocations and several dislocations of pure screw or mixed character showed no clearly distinguishable etch pits, whereas several dislocations with screw component showed large etch pits with diameters of about 0.5 μm. These are assumed to be etch pits associated with open core dislocations or nanopipes. In samples containing a SiN_x micromask, preferential bending of edge type threading dislocations at the SiN_x interlayer was observed, which is in contrast to the results found for GaN grown on silicon [Contreras et al., Appl. Phys. Lett. **81** (2002) 4712]. This might be attributed to the different strain state of GaN grown on silicon or sapphire, as revealed by temperature dependent X-ray diffraction (XRD).

Y5.23

Measuring Non-uniformities in GaN/AlN Quantum Wells using STEM. K. Andre Mkhoyan[1], H Wu[2], W J Schaff[2], L F Eastman[2] and J Silcox[1]; [1]Applied Physics, Cornell University, Ithaca, New York; [2]School of Electrical and Computer Engineering, Cornell University, Ithaca, New York.

Recent increased interest in GaN/AlGaN quantum wells (QWs) is primarily governed by possibilities of the fabrication of new opto-electronic devices such as optical modulators, switchers, etc. The mobility and distribution of the carriers in these structures are strongly dependent on the roughness of the quantum wells as well as on the sharpness of their interfaces. Reliable measurement of the uniformity of these QWs is needed. For characterization of these GaN/AlGaN QWs, when the width of the wells is as small as 10-15 Å, scanning transmission electron microscopy with ~ 2 Å probe is ideal for these type of measurements. The samples of wurtzite GaN/AlN QWs studied here were grown in an MBE system and consist of 20 GaN/AlN QWs with initially estimated 60 Å AlN barrier layers and 12-14 Å GaN wells. Composition sensitive annular dark field imaging and electron energy-loss spectroscopy (EELS) were used to determine long-range uniformities of GaN quantum wells and the sharpness of their interfaces as grown in an AlN matrix by molecular beam epitaxy. Low magnification annular dark field images reveal waviness along the growth plane with a period of ~50 nm and a height ~20 nm in one sample and significant changes of the long-range uniformity in the other. Measurements of the changes in energy-loss spectra of the Al L2,3-edge, Ga L2,3-edge and N K-edge across quantum well indicate that the interfaces between the QWs and the barriers are in most cases almost atomically sharp while in some cases they are not. For a better understanding of the measured EELS data mulislice simulations of the interaction of an incident electron beam with specimen were also performed to calculate beam spreading inside the sample.

Y5.24

TEM Analysis of Polarity of GaN Grown by MOHVPE on

GaAs(111)A and (111)B. Noriyuki Kuwano[1,2], Y. Ohnishi[2], Nao Murakami[3], Y. Kangawa[3], Y. Kumagai[3] and A. Koukitu[3]; [1]KASTEC, Kyushu University, Kasuga, Fukuoka, Japan; [2]Dept. Adv. Sci. Electr. Mater., Kyushu University, Kasuga, Fukuoka, Japan; [3]Dept. Appl. Chem., Tokyo Univ. Agr. Tech., Koganei, Tokyo, Japan.

Gallium arsenide (GaAs) (111) is a very attractive substrate for growing a free-standing GaN, However, crystals of GaAs and GaN do not have inversion symmetry either, and then they have a polarity along (111) and (0001), respectively. Since the growth process of GaN depends strongly upon the surface structure, the polarity along the growth direction is important to control the quality of GaN crystals. In this work, GaN layers were grown by the metalorganic hydride vapor phase epitaxy (MOHVPE) method on both sides of GaAs(111)A and (111)B. The growth temperatures were 550°C for a buffer layer about 100 nm thick and 850 or 950°C for a GaN layer about 8 μm. TEM observation was performed to analyze the microstructure of the GaN layers. The polarity of GaN was examined by the convergent beam electron diffraction (CBED) method. The buffer layer was found to grow in zincblende structure with stacking faults. The GaN layer grown at 850°C is made of columnar wurtzite crystals containing many stacking faults parallel to (0001), The wurtzite GaN layers were confirmed to have Ga-polarity along the growth direction irrespective of the polarity of substrate plane. The GaN layer grown at 950°C is made of zincblende structure in the lower part and wurtzite structure in the upper. The wurtzite part contains few stacking faults and has Ga-polarity along the growth direction. The zincblende-part was revealed to have a polarity corresponding to the one of the substrate plane. The results implied that at a high temperature the wurtzite crystal grows discontinuously on the zincblende GaN. The change in stacking order and the inversion of polarity are also discussed.

Y5.25

Plan-view TEM Imaging of Vertical Threading Dislocations in (0001) GaN. David M. Follstaedt[1], Nancy A. Missert[2], Daniel D. Koleske[3], Christine C. Mitchell[3], Karen C. Cross[3], Michael P. Moran[1] and Andrew A. Allerman[3]; [1]Dept. 1111, Sandia National Laboratories, Albuquerque, New Mexico; [2]Dept. 1112, Sandia National Laboratories, Albuquerque, New Mexico; [3]Dept. 1126, Sandia National Laboratories, Albuquerque, New Mexico.

GaN has important electronic and optical properties for new devices, but to achieve the performance needed, vertical threading dislocations (VTDs) must be removed. To determine progress, VTD densities must be accurately measured, both the total and individual densities for edge, screw and mixed dislocation types in order to understand their separate effects on performance. TEM is generally taken as reliable for detecting dislocations, and VTDs can be detected in plan-view of (0001) GaN using g = (11-20) diffraction conditions. This condition is often thought to detect edge (Burgers vector b = a) and mixed (b = a+c) VTDs, but not screw (b = c) VTDs because g.b = 0 for them. This dot product examines the alignment of the strain around a dislocation passing through the specimen with the diffracting lattice planes; zero indicates the dislocation is invisible. We demonstrate that screw and mixed VTDs have a second contrast mechanism due to strain relaxation at the top and bottom surfaces of the TEM specimen. Surface relaxation contrast was seen much earlier by Tunstall et al. (Phil. Mag. 9, 99(1964)). We also detect strain contrast along dislocation lines for edge and mixed VTDs since g.b is non-zero. Together, the two mechanisms allow us to identify the type of individual VTDs. We have determined that a 2-beam diffraction condition with g = (11-20) and large tilt (~18 degrees) allows all VTDs to be counted; an insufficient tilt is likely to miss edge VTDs. We have applied this method to GaN grown with delayed 3D->2D recovery produced by reducing NH3 flow after low-temperature nucleation on sapphire, and measured a total density of 4.6-6.1x10^8 VTDs/cm^2. We are examining VTD densities for other growths using TEM specimens with broad thinned areas, and are comparing to densities obtained with AFM and cathodoluminescence, which are lower. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94-AL85000.

Y5.26

Effect of threading dislocation density on microstructure and optical properties of InGaN epilayers. Sridhar Srinivasan[1], Lijian Geng[1], Fernando A Ponce[1], Shinji Tanaka[2] and Yukio Narukawa[2]; [1]Department of Physics and Astronomy, Arizona State University, Tempe, Arizona; [2]Nichia Corporation, 491 Oka Kaminaka Anan, Tokushima-ken 774-8601, Japan.

Threading dislocations are known to play an important role in determining the properties of InGaN films grown on GaN. Previous studies have shown the optical properties of InGaN alloys to be closely related to surface morphological defects that are associated with threading dislocations in the underlying GaN layer. In this work, we have studied the microstructure and optical properties of InGaN layers grown on two different GaN layers having different threading dislocation densities. One is standard GaN on sapphire and the other is epitaxially laterally overgrown GaN (ELOG). Two distinct mechanisms of strain relaxation are observed. InGaN epilayers on GaN are fundamentally pseudomorphic and undergo elastic relaxation by the evolution of threading dislocations into pyramidal defects. On the other hand, epitaxy on ELOG shows that, in the absence of threading dislocations, the film undergoes systematic plastic relaxation by a slip process. Periodic arrays of misfit dislocations are observed at the InGaN/GaN interface. Composition measurements by RBS indicate that plastic strain relaxation allows incorporation of more indium into the film for the same In/Ga ratio in the gaseous reactant mixture. Significant improvement in optical properties is also observed. InGaN films grown on ELOG exhibit twice the luminescence intensity and a more Gaussian peak compared to those grown on regular GaN. Departures from Gaussian behavior in InGaN are due to a low-energy peak associated with In-rich regions. These regions have been shown to be in the vicinity of pits, which nucleate at threading dislocations. Reduction in threading dislocation density results in a smaller intensity of the low-energy peak. This work underlines the role of threading dislocations in strain relaxation mechanisms and optical properties of InGaN epilayers.

Y5.27

Electrical Characterization of Carbon-Doped GaN Grown by Molecular Beam Epitaxy Using Thermally Stimulated Current Spectroscopy. Zhaoqiang Fang[1], David C Look[1], Rob Armitage[2,3], Qing Yang[2,3] and Eicke R Weber[2,3]; [1]Semiconductor Research Center, Wright State University, Dayton, Ohio; [2]Department of Materials Science and Engineering, University of California, Berkeley, California; [3]Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California.

Understanding the properties of carbon-related defects in GaN is necessary to evaluate the influence of residual C comtamination on the material properties. In this study, GaN:C layers were grown on semi-insulating (SI) MOCVD-GaN templates by plasma-assisted MBE in Ga-rich conditions using CCl_4 as a doping source. Three samples, including a SI MOCVD-GaN sample, were characterized by using SIMS, resistivity, and thermally stimulated current (TSC) spectroscopy. As [C] increases from 3 x 10^{17} cm^{-3} in the MOCVD-GaN to 2 x 10^{18} and 2 x 10^{19} cm^{-3} in the lightly and heavily C-doped MBE-GaN samples, resistivity reduces from about 1 x 10^8 to 1 x 10^7 and 1 x10^5 Ωcm, and activation energy of resistivity or dark current decreases from 0.70 eV to 0.63 and 0.33 eV. In the SI-MOCVD sample, we find at least six TSC traps, B (0.63 eV), B_x (0.51 eV), C_1 (0.44 eV), C (0.32 eV), D (0.23 eV), and E (0.16 eV), which are very similar to electron traps often found in n-type GaN films by using deep level transient spectroscopy. However, in the MBE-GaN sample with the lowest value of [C], the only observed traps are B and E, and the relative trap density of trap E over trap B is significantly reduced. However, in the MBE-GaN sample with the highest value of [C], both traps E and B are suppressed, and instead, trap B_x is prominent. Based on the studies of deep centers induced by electron-irradiation and reactive ion etching, we believe that E, D and C are related to V_N and B might be related to V_{Ga}. Incorporation of [C] in GaN introduces C_N acceptors, resulting in compensation and formation of SI-GaN; however, more [C] cause suppression of V_N. As even more [C] is incorporated, the concentration of acceptors introduced by C-doping actually *decreases*. This is attributed to incorporation of an increasingly large fraction of total carbon in the form of C_{Ga} or a related complex. The heavily C-doped GaN sample also exhibits very stron photocurrent and persistent photoconductivity at 83 K. These phenomena can perhaps be related to the presence of C_{Ga} DX-donors.

Y5.28

Microstructure of Nonpolar a-Plane GaN Grown on (11$\bar{2}$0) 4H-SiC. Dmitri N Zakharov[1], Zuzanna Liliental-Weber[1], Brian Wagner[2], Zach J Reitmeier[2], Edward A Preble[2] and Robert F Davis[2]; [1]Lawrence Berkeley National Laboratory, Berkeley, California; [2]North Carolina State University, Raleigh, North Carolina.

III-V nitrides have received much interest as a promising material for laser diodes and light emitting diodes. Many studies have shown the presence of spontaneous and piezoelectric polarization within the GaN-based active layers. The total polarization is aligned along [0001] direction. This polarization leads to high interface charge densities and spatial separations of electron and holes wave functions in quantum well structures, which alters optoelectronic properties of devices. One of the possible solutions to eliminate these effects is to grow GaN-based layers in nonpolar directions. In this paper the microstructure of the 1 μm thick (11$\bar{2}$0) (a-plane) GaN grown on 4H-SiC substrate with AlN buffer layer will be presented. These nonpolar GaN layers are grown by organometallic vapor phase epitaxy at 1015°C. Plan-view and cross-section samples are studied by

transmission electron microscopy. Cross-section images reveal crack formation. Cracks start in GaN approximately 100nm from the buffer layer and propagate to the sample surface. Threading dislocations with the density of $\sim 4.0 \times 10^{10} cm^{-2}$ and stacking faults (SFs) are also observed. These dislocations are mainly partial dislocations which terminate SFs. The density of SFs is $\sim 1.6 \times 10^{6}$ cm^{-1}, as derived from plan-view images. High resolution electron microscopy shows that majority of SFs are I_1 type low-energy planar defects. In some cases SFs with higher formation energy are also observed. Microstructure and defect formation mechanism will be discussed in conjunction with epitaxial growth process.

Y5.29

Structural Study of V-like Columnar Inversion Domains in AlN Grown on Sapphire. Jacek Jasinski[1], Tomasz Tomaszewicz[1], Zuzanna Liliental-Weber[1], Qing Sun- Paduano[2] and David W Weyburne[2]; [1]Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California; [2]Air Force Research Laboratory, Hanscom AFB, Massachusetts.

C-plane sapphire often remains the substrate of choice for epitaxial growth of III-nitrides films. However, due to the large lattice and thermal expansion coefficient mismatch high densities of structural defects is formed inside such nitride films. Different types of structural defects (threading dislocations, dislocation loops, basal stacking faults, nanopipes, and inversion domains) in GaN grown on sapphire have been addressed by numerous studies. On the other hand, much less has been done in case of AlN films grown on sapphire despite the growing interest in their potential applications in high power and high temperature devices. Here in this paper we will report on structural study of V-shape columnar defects formed inside AlN films grown on nitridated c-plane sapphire substrates. It will be shown that these defects correlate with small islands on the surface that are observed by atomic force microscopy (AFM). Moreover, with use of different techniques of transmission electron microscopy (TEM) we identified these defects as inversion domains, e.g. V-shape columns of AlN grown with opposite polarity. Strong experimental evidence will be provided to support this identification. The absolute polarity of these inversion domains will be also analyzed and the model of inversion domain boundaries will be discussed.

Y5.30

Defects In Non-Polar A-Plane GaN Films On R-Plane Sapphire Substrates. Jinwei Yang, Changqing Chen, jianping Zhang, Wenhong Sun, Hongmei Wang, Mikhail Gaevski, Vinod Adivarahan and M Asif Khan; Depart. of Elect. Engr., Uni. of South Carolina, Columbia, South Carolina.

Recently, high quality non-polar a-plane GaN films have been successfully grown on R-plane sapphire substrates. Significant quality improvements have resulted from epitaxial lateral overgrowth (ELOG) and selective area lateral epitaxy (SALE) procedures. Both the SALE and the ELOG processes lead to much lower dislocation densities and smooth growth surfaces. We now report TEM defects analysis on conventional low pressure MOCVD grown planar a-plane GaN templates, and fully coalesced ELOG and SALE films. For this study, (11-20) plan view and (1-100) and (0001) cross section TEM foils were prepared. Dislocation densities as high as 5x10(10)/cm2 were measured for the a-plane GaN template samples. For the ELOG samples, it remains the same for the window area but reduces dramatically for the wing area material. For the fully coalesced a-plane GaN films from SALE, the dislocation density reduced to below our TEM measurement limit. AFM images of the SALE sample surfaces, etched to reveal dislocations, were about 10(5)/cm2. Stacking faults were found to be present both in the ELOG and the SALE a-plane GaN films. We will present the details of the ELOG/SALE growth procedures and a model that explains the mechanism of stacking fault formation in them.

Y5.31

Formation of Defects in GaN Grown by HVPE on a SiC Substrate. Leonid A. Bendersky[1], Denis V Tsvetkov[2] and Yuriy V Melnik[2]; [1]NIST, Gaithersburg, Maryland; [2]Technologies and Devices International, Inc.12214 Plum Orchard Dr., Silver Spring, MD 20904, USA, Silver Spring, Maryland.

A defected zone in the HVPE-deposited GaN was investigated by transmission electron microscopy (TEM) of cross-section and plan-view specimens. The TEM structural analysis has shown that the defected zone is formed during the process of nucleation, coalescence and overgrowth of three-dimensional islands. The islands differ by a non-equivalent translation with respect to the reference (substrate) lattice, and therefore their coalescence results in formation of translational (stacking fault-type) boundaries. For the processing conditions used in the direct HVPE deposition, it appears that the islands adapt a shape of {1121}-faceted truncated pyramids. Continued coalescence and overgrowth of the crystallographically non-equivalent grains result in a substructure of connected (0001) and {1120} stacking faults, as well as in threading dislocations. A density of these defects decreases as the growth of GaN progresses, thus determining the thickness of the defected zone. Extend of the defected zone depends on nucleation frequency and anisotropic growth rate of different crystallographic facets.

Y5.32

The microstructure and polarity of GaN nucleation layers grown by MOCVD on a-plane sapphire. Tomasz Wojtowicz[1], Pierre Ruterana[1], Gerard Nouet[1], Mark E. Twigg[2], Rich L. Henry[2], Dan D. Koleske[3] and Alma E. Wickenden[4]; [1]LERMAT, ENSICAEN-ISMRA, Caen, Normandy, France; [2]Electronics Science and Technology Division, NRL, Washington, District of Columbia; [3]Sandia National Laboratories, Albuquerque, New Mexico; [4]Army Research Laboratory, Adelphi, Maryland.

For the last decade, GaN and related compounds have been of great interest due to the development of applications such as high brightness light-emitting diodes and laser diodes operating in the blue/green to ultraviolet range. Significant progress has been achieved in the growth process of GaN. Most of the work done on GaN has taken into account layers grown on the (0001) sapphire plane. However one would expect the growth on the (11-20) plane to lead to different structural defects. As has been shown, in one direction, the mismatch is rather small. In this work, we have carried out structural analysis of nucleation layers grown at temperatures ranging from 600 C to 1100 C. In addition we have investigated layers nucleated at the temperature of 1028 C by varying the pressure and we tried to monitor the growth mode. It is shown that structural parameters, such as the orientation relationships, the layer morphology and the nucleation mechanism critically depend on the growth temperature. At the lowest temperatures, the growth is completely three-dimensional, with a mixture of the two traditional orientation relationships, and with a small value of film thickness necessary to achieve coalescence. The A: [10-10]sap//[11-20]GaN orientation relationship predominates and the layer roughness tends to slightly decrease. The A orientation relationship is never perfect and there is always 1.5 degree misorientation from the same direction in sapphire, whereas the B: [10-10]sap//[10-10]GaN orientation is always perfect. When the temperature increases, there is a competition between the lateral and vertical growth. For the highest growth temperatures, the lateral growth is the dominant mechanism and the nucleated layers are completely flat with the A orientation. However, they are found to contain a quite large number of defects such as inversion domains. It is concluded that the growth morphology and epitaxial relationships, as well as the associated defects, may be directly controlled by tailoring the growth conditions. Because the growth was directly deposited on the sapphire surface, we have also investigated the evolution of the layer polarity using CBED analysis.

Y5.33

Dislocation Morphology Evolution in Si-Doped AlGaN/GaN Multiple-Quantum-Well. Rong Liu[1], F A Ponce[1], S-L Sahonta[2], D Cherns[2], H Amano[3] and I Akasaki[3]; [1]Department of Physics and Astronomy, Arizona State University, Tempe, Arizona; [2]H. H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom; [3]Department of Materials Science and Engineering, Meijo University, Nagoya, Japan.

AlGaN/GaN multiple-quantum-well (MQW) structures are typically used in ultraviolet light emitting devices. The GaN active layer structures have much lower quantum efficiency than devices with InGaN as the active layer due to a stronger non-radiation effect of the dislocations. Silicon-doping of the AlGaN barriers has been found to substantially increase the luminescence efficiency. However, if the carrier concentration exceeds 4x10E19 cm-3, the quantum efficiency decreases. In this work, a TEM study was performed on a set of samples with increasing doping level in order to understand the effect of doping on the dislocation morphology. Cross-section and plan-view images show that nanopipes change to full-core dislocations when they propagate through Si-doped MQW structures. We believe that modulation of the strain field due to Si-doping is responsible for the core-structure evolution. This observation is important because nanopipes are believed to shorten device lifetime by creating short circuits. Si-doping also affects the surface morphology of the samples. Cross-sectional images indicate that all dislocations, regardless of their nature (edge, screw or mixed), open up as surface pits due to Si-doping. Samples without Si-doping do not exhibit these surface pits. The pit size increases with the doping concentration. At low doping levels, formation of the pits occurs after several periods of growth of the MQW. In these samples, nanopipes change to full-core dislocations and then open up as surface pits when they propagate through the MQW. In the highly-doped sample, however, the pits form at the beginning of the MQW growth. Morphology of the pits changes from hexagonal to circular funnel shape with increasing doping levels. Although Si-doping improves the quantum efficiency of

the devices, degradation of the microstructure due to the impurity compromises the effect as the doping level increases to 10E20 cm-3.

Y5.34

Structural Units and Energy of Grain Boundaries in GaN. Gerard Nouet, Pierre Ruterana and Jun Chen; LERMAT, ENSICAEN, Caen, France.

GaN layers grown by MBE or MOCVD contains a high density of threading dislocations. They may form low-angle and high-angle grain boundaries. The atomic structure of the 1/3<11-20> edge dislocation was previously investigated by HREM and atomic calculation. This dislocation may present three different cores corresponding to the 4, 57 or 8 atom ring. The tilt grain boundaries around <0001> are constructed with the same dislocations and these three cores were identified by HREM in these grain boundaries. The potential energy of these grain boundaries in the range 0-60 degrees was calculated by using the Stillinger-Weber potential after modification to take into account the Ga-Ga and N-N wrong bonds present in the core of the defects. In this work, the energy of other grain boundaries corresponding to the dingonal of the unit cell of the coincidence site lattice have been calculated.The comparison with the first results corresponding to the edges of the unit cell shows that the energy depends on the type of structural units used to construct the grain boundary. The 57 atom ring leads to energy values lower than the 57+57- atom ring. This difference may be explained by considering the Burgers vector associated with the structural units. For the 57 atom ring, the Burgers vector is normal to the grain boundary plane whereas the 57+57- atom ring is charasterised by a 60 degree Burgers vector leading to a residual stress in the boundary plane.This suppementary stress is expected to be at the origin of the largest energy values calculated for the configurations involving the 57+57- atom ring.

Y5.35

Phase Separation and Atomic Ordering in InGaN Mixed Layers. Manu Rao, Daewoo Kim, Yongqian Wang and Subhash Mahajan, Chemical & Materials Engineering, Arizona State University, Tempe, Arizona.

Atomic ordering has been mainly observed in InGaN layers grown by MBE but has been reported in layers grown by MOCVD. Phase separation has been observed to occur in alloys with higher In contents. Phase separation and ordering affect properties such as the mobility, band-gap and luminescence behavior and therefore are of significant interest. The mechanisms responsible for the evolution of the ordered structures and the relationship with phase separation are not well understood in InGaN layers. Using MOCVD, thin GaN nucleation layers were deposited on (0001) sapphire substrates at low temperature followed by annealing. The annealing resulted in a change in the microstructure to give larger islands bounded by {10-11} facets. In one sample a thick GaN buffer layer was then deposited, which planarized the surface, and this was followed in all samples by growth of InGaN. Layers containing 22% and 28% InN with thicknesses of 200nm and 600nm were deposited. Diffraction patterns of [10-10] cross sections were taken using TEM to detect evidence of atomic ordering and phase separation. The results show evidence for atomic ordering. The (0001) spot is a systematic extinction in the [10-10] diffraction pattern. However, this and equivalent superlattice spots were present when InGaN was deposited on annealed nucleation layers but not when deposited on GaN buffer layers. Therefore, {10-11} surface facets are likely responsible for formation of the ordered structure. The superlattice spots were present only in thicker InGaN films, suggesting that the structure is only weakly ordered. Phase separation was detected in all samples in this series. Spots in the diffraction patterns exhibit satellites oriented in <1-210> directions relative to the fundamental reflections. The wavelengths of these composition modulations were calculated to be 8-10nm. The support of this work by NSF is gratefully acknowledged.

Y5.36

Analysis of InGaN-GaN Quantum Well Chemistry and Interfaces. Tim M. Smeeton[1], M J Kappers[1], J S Barnard[1], D M Graham[2], P Dawson[2] and C J Humphreys[1]; [1]Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom; [2]Department of Physics, UMIST, Manchester, United Kingdom.

In the past, the localisation of excitons in InGaN/GaN quantum wells has been attributed both to indium composition fluctuations (indium "clustering") and to very small variations in the widths of the wells. We have studied a range of InGaN quantum well samples using high resolution transmission electron microscopy (HRTEM), high angle annular dark field-scanning TEM (HAADF-STEM; including results from an aberration corrected STEM), high resolution X-ray diffraction (HRXRD) and X-ray reflectivity (XRR). The material was grown by MOVPE using a close coupled showerhead reactor with InGaN growth temperatures between 700 °C and 750 °C. Detailed photoluminescence (PL) measurements indicate that localisation occurs on a length scale of about 2 nm and that our samples have a high PL internal quantum efficiency (for example of 43% for a multiple quantum well structure with room temperature peak emission of 486 nm). Our evidence suggests that these InGaN layers do not exhibit the kind of gross indium clustering which other workers have reported for their material. However, from multiple characterisation techniques we detect clear evidence for asymmetry in the widths of the interfaces of the quantum wells. While the GaN-InGaN lower interface seems to be fairly abrupt, the InGaN-GaN upper interface is more graded. This is indicative either of atomic scale roughening during the thin InGaN layer growth or delayed indium incorporation into the GaN barrier once the indium source has been switched off. Contrary to the prevailing opinion in the literature, it seems probable that exciton localisation in these samples is not due to strong variations in the alloy composition.

Y5.37

Deep Defects In Fe-Doped GaN Layers Analysed By Electric And Photoelectric Spectroscopic Methods. Hartmut Witte, Kevin Fluegge, Andre Krtschil, Armin Dadgar, Alois Krost and Juergen Christen; Institute of Experimental Physics, University of Magdeburg, Magdeburg, Germany.

Insulating GaN layers are essential for applications in high-frequency and high-voltage devices. Iron doping of the GaN layers is a useful approach to produce the semi-insulating properties, however, this changes the concentration of deep defect levels and introduces additional impurities. In addition, detailed knowledge of the complex compensation mechanisms in iron-doped GaN layers is scarce up to now. We have analyzed defects in Fe-doped GaN layers grown by metal-organic vapor phase epitaxy on sapphire as well as on Si substrates using temperature-dependent Hall effect (TDH), photocurrent spectroscopy (PC), thermal admittance spectroscopy (TAS), thermally stimulated currents (TSC), as well as deep level transient spectroscopy (DLTS). In Si-doped and Si -Fe co-doped GaN layers we found a strong compensation effect in our TDH measurements as well as changes in the defect spectrum determined by DLTS and TAS. With increasing Fe-doping level the resistivity increases. A p-type conductivity is obtained for high Fe content and a dominant acceptor with an activation energy of about (450±40) meV is found in TDH. In the PC and TSC spectra deep defect-to-band transitions and defect emissions at energies between 0.8eV and 0.9 eV were observed which are related to Fe defect states. In the n-type Fe-doped samples other traps with activation energies at 350 meV and 600 meV were detected by TAS and TSC, whereas shallower defect states were found to be suppressed. Quenching effects caused by an additional sub-band gap illumination vanishes with increasing Fe incorporation. Based on these results, the influence of the Fe doping of the compensation mechanism will be discussed in detail.

Y5.38

Identification of Carbon-related Bandgap States in GaN Grown by MOCVD. Andrew Michael Armstrong[1], Aaron R. Arehart[1], Brendan Moran[2], James S. Speck[2], Umesh K. Mishra[2], Steven P. DenBaars[2] and Steven A. Ringel[1]; [1]Electrical Egineering, The Ohio State University, Columbus, Ohio; [2]Materials Department and Electrical and Computer Engineering Department, University of California, Santa Barbara, Santa Barbra, Ohio.

Carbon doping of GaN is of great interest in part because it has been shown to result in semi-insulating behavior. However, determination of the bandgap states and hence the exact mechanism responsible for the SI behavior is, to date, an unresolved issue. A key impediment is that the presumed C acceptor levels are likely near the minority carrier (valence) bandedge of otherwise background n-type GaN, and hence their precise detection by usual methods is difficult. In this paper, we exploit the inherent ability of deep level optical spectroscopy (DLOS) to detect states near the minority carrier band edge, as well as potentially deep states associated with C in background n-type GaN. This is accomplished by comparing unintentionally doped (uid) GaN grown by atmospheric pressure (AP) MOCVD, which has a residual n-type conductivity, with LP MOCVD GaN that incorporates a large concentration of C for both uid and intentionally Si co-doped conditions. The results show the emergence of a shallow state at E_c - 3.28 eV (E_v + 0.16 eV) for the LP samples with a minimum concentration of 3.6×10^{16} cm^{-3} that efficiently compensates Si donors for the co-doped sample, and results in semi-insulating behavior for the uid LP sample. In contrast, this state is not observed for the AP GaN material, which incorporates a factor of ~10 times less C, and instead only the expected residual Mg acceptor level at E_c - 3.22 eV is observed. Additionally, a state at E_c - 1.35 eV, near the theoretically expected C split-interstitial level in n-type GaN, is observed to increase significantly in concentration with increased C concentration. The relation between the presence of C and both shallow and deep states throughout the GaN bandgap for

both LP and AP MOCVD growth will be discussed.

Y5.39
Band Bending near the Surface in GaN as Detected by a Charge Sensitive Probe. Shariar Sabuktagin, Michael A. Reshchikov, Ali Teke, Seydi Dogan, Joshua Spradlin, Daniel Johnstone and Hadis Morkoc; Electrical Engineering, VCU, Richmond, Virginia.

GaN-based optical and electronic devices have progressed rapidly in recent years. However only a little attention has been given to the affect of the surface on the properties of GaN and related devices. It is well known that the surface of undoped GaN, both atomically clean and *practical* (chemically cleaned, air-exposed), exhibit an upward band bending of the order of 1 eV [1]. It is also known that a thin oxide layer, as well as desorbed oxygen atoms, covers the GaN surface. We measured the absolute value of surface band bending with Dimension 3100 atomic force microscope in the surface potential mode. Platinum coated tips were calibrated with respect to a 100 nm gold film. Surface potential measurement on our GaN samples showed an upward band bending of about 0.7 eV. The samples stored in dark for one week showed an increase in band bending by up to 0.1 eV. The effect of UV exposure (with a pulse nitrogen laser) on band bending was studied in detail for selected samples. Typically, the surface barrier decreased by about 0.2 eV and the decrease saturated at excitation intensities above 10^{13} photons per pulse. Very slowly (by a logarithmic law) the barrier got restored in dark at room temperature. These and other similar phenomena are preliminarily explained by the combination of photo-induced desorption of oxygen from the surface and thermionic transfer of free electrons from the bulk to the surface states. [1] V. M. Bermudez, J. Appl. Phys. 80, 1190 (1996).

Y5.40
Reciprocal Space Mapping of X-Ray Diffraction Intensity of GaN-Based Laser Diodes Grown on GaN Substrates. Koichi Tachibana, Yoshiyuki Harada, Shinji Saito, Shinya Nunoue, Hiroshi Katsuno, Chie Hongo, Genichi Hatakoshi and Masaaki Onomura; Corporate R&D Center, Toshiba Corp., Kawasaki, Japan.

We clearly show the difference in reciprocal space mapping (RSM) of x-ray diffraction (XRD) intensity of GaN-based laser diodes (LDs) on various GaN templates such as GaN/sapphire and GaN substrates. The tilt distribution, derived from the RSM of XRD intensity of the LDs grown on GaN substrates, is smaller than that of the LDs grown on GaN/sapphire. This result indicates GaN substrates are favorable to realize the superior LD characteristics. The LDs have the same structure of separate-confinement-heterostructure except for substrates: GaN substrate and GaN/sapphire. The RSM was recorded of x-ray intensity around the asymmetric (10-15) diffraction from the LD structures grown on GaN substrate and GaN/sapphire. The incident beam was the x-ray with CuKα1 radiation (λ = 0.154056 nm) through the asymmetric four-crystal Ge (220) monochromator. AlGaN and InGaN were fully strained, from the RSM of the LDs both on GaN substrate and GaN/sapphire. However, the distribution of XRD intensity in these maps was quite different. The full width at half maximum in ω-scan of XRD from the LDs on GaN substrate was reduced to be as small as 60%, compared with that value of the LDs on GaN/sapphire. Therefore, it was found that the tilt distribution of the LDs on GaN substrate, corresponding to the broadening of ω-scan, was smaller than that on GaN/sapphire. We will demonstrate the device characteristics of these LDs at the meeting.

Y5.41
Thermal Stability of Iridium Schottky Contacts on n-$Al_xGa_{1-x}N$. Almaz Kuliev, Deepak Selvanathan, Vipan Kumar, Seiyon Kim, Gabriel Cueva and Ilesanmi Adesida; Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois.

Group III-nitride semiconductors offer great promise for high-power and high-temperature applications due to the materials' superior electronic properties. In this report, we will present results on the development of thermally stable Schottky contacts for high-temperature applications. The effects of rapid thermal annealing on the electrical and materials characteristics of iridium Schottky contacts on n-type GaN and $Al_{0.25}Ga_{0.75}N$ were investigated. Effective barrier heights were obtained from current-voltage (I-V) and capacitance-voltage (C-V) measurements for diodes upon annealing in nitrogen ambient at temperatures varying from 400 °C to 850 °C. Electrical characteristics (effective barrier height, ideality factor and reverse leakage current) of iridium diodes on $Al_{0.25}Ga_{0.75}N$ were found to be stable for annealing temperatures up to 700 °C, while the diodes on GaN exhibited degradation at 500 °C. We will present results from further examination of the annealed Ir/$Al_xGa_{1-x}N$ systems on depth profiling by means of Auger electron spectroscopy as well as the detection of possible intermetallic and interface reaction products by x-ray diffraction (XRD) and x-ray photoelectron spectroscopy (XPS), respectively. Results show the potential for using iridium Schottky contacts for the fabrication of GaN-based transistors for high-temperature applications.

Y5.42
High reflective Ni/Au ohmic contact on p-type GaN using Ag reflector for flip-chip LEDs. Soo Young Kim, Hak Ki Yu, Ho Won Jang and Jong-Lam Lee; Department of Materials Science and Engineering, Pohang University of Science and Technology (POSTECH), Pohang, South Korea.

Nitride semiconductors are crucial materials for short-wavelength optoelectronic devices, such as light-emitting diodes (LEDs), photodetectors, laser diodes and so on. In conventional top-emission LEDs, a large fraction of photons generating from AlGaN|InGaN multi quantum well is absorbed by the p-electrodes and bonding pads, reducing external quantum efficiency. In order to improve the external quantum efficiency and current spreading problem, fabricating a flip-chip type LEDs has been attempted. An achievement of low resistant and high reflective p-electrode is crucial for large area flip-chip LEDs. In this letter, we report an oxidized Ni|Au|ITO|Ag ohmic contact with a low resistance and high reflectance on p-type GaN. For the evaluation of contact resistivity on p-type GaN, TLM test structure was formed. Ni (20 Å) and Au (30 Å) metals were deposited in sequence by electron beam evaporator, followed by pre-annealing the Ni|Au metals at 500 °C under O_2 ambient (reference sample). Then, the sample was made by depositing of ITO (600 Å) film on the reference sample by RF magnetron sputtering, followed by depositing Ag or Al (600 Å) by thermal evaporator. After annealing at 500 °C under O_2 ambient, a specific contact resistivity as low as 3.2×10^{-5} Ωcm^2 was obtained. The reflectance of Ni|Au|ITO|Ag contact was higher about 15 % than that of Ni|Au one. X-ray diffraction profiles and Auger electron depth profiles showed that the ITO layer acts as a diffusion barrier for indiffusion of Ag into the Ni|Au layers, providing the low resistant and high reflective ohmic contact on p-type GaN for flip-chip light emitting diodes. Therefore, it is considered that Ni|Au|ITO|Ag contact could be a promising p-electrode for a reflective ohmic contact to GaN-based flip-chip LEDs.

Y5.43
GaInN Light-Emitting Diodes with Omni-Directional Reflectors Using Rare-Earth Metal Oxides. Jong Kyu Kim, Thomas Gessmann, Yun-Li Li and E F Schubert; ECSE, Rensselaer Polytechnic Institute, Troy, New York.

A novel GaInN light-emitting diode (LED) structure employing an omni-directional reflector (ODR) using rare-earth conducting metal oxides is presented. The triple layer of the ODR consists of p-type GaN, quarter-wavelength thickness of RuO_2 or IrO_2 and silver layer. The RuO_2/Ag and the IrO_2/Ag contacts serve as ohmic contacts to the p-type GaN. It is shown that the ODR-LEDs have higher light-extraction efficiencies, better electrical properties and thermal stabilities than the LEDs with conventional Ni/Au contacts and ITO/Ag contacts. The GaInN LED structure was grown by metal-organic chemical vapor deposition on c-plane sapphire substrate and consists of a thick n-GaN buffer layer, an n-GaN lower cladding layer, a GaInN/GaN multiple quantum well active region, a p-GaN upper cladding, and a highly doped contact layer. LED mesa structures were obtained by dry-etching. Ti/Al/Ni/Au ohmic contacts to n-GaN were deposited and annealed at 600 °C under N_2 ambient. Then, Ru or Ir was deposited on p-GaN and annealed at 500 °C under O_2 ambient to form quarter-wavelength thickness of RuO_2 or IrO_2, respectively. Finally, Ag reflecting layers were deposited. For comparison, LEDs with conventional Ni/Au and ITO/Ag contacts on p-type GaN were fabricated on the same wafer. High-resolution x-ray diffraction and x-ray photoemission spectroscopy results show that metallic Ru and Ir contacts transformed to virtually transparent RuO_2 and IrO_2 after the oxidation annealing. RuO_2 and IrO_2 contacts to p-type GaN show much lower contact resistivities than ITO/Ag contacts and are comparable to conventional Ni/Au contacts. In addition, the light power extracted from the ODR-LEDs is significantly larger than that from conventional LEDs. This can be attributed to better light extraction efficiency due to the use of RuO_2/Ag or IrO_2/Ag omni-directional mirrors. Furthermore, RuO_2 and IrO_2 layers restrain the degradation of contacts due to the diffusion of silver into p-type GaN surface at an elevated temperature, leading to a good thermal stability of the GaInN ODR-LEDs.

Y5.44
High Quality Metal/Tin Oxide Ohmic Contacts to p-type GaN. Dong-Seok Leem[1], J. O. Song[1], H.-G. Hong[1], J. S. Kwak[2], O. H. Nam[2], Y. Park[2] and T-Y. Seong[1]; [1]Department of Materials Science and Engineering, Kwangju Institute of Science and Technology (K-JIST), Kwangju, 500-712, South Korea; [2]Photonics Lab., Samsung Advanced Institute of Technology, Suwon, 440-600, South Korea.

Formation of high quality ohmic contacts to p-GaN is one of the key issues for the further improvement of the performance of optical devices such as high power LEDs and LDs. Oxidized Ni/Au contacts are currently being used as ohmic contact electrodes for commercial LEDs. However, this contact is required to improve thermal stability and transparency. Recently, reliable ohmic metallization schemes using transparent conducting oxides (TCOs), such as indium tin oxide (ITO) and Al-doped zinc oxide (AZO), have been investigated. In particular, the use of AZO (450nm) was found to be fairly effective in improving the electrical and optical properties of ohmic contacts. In this work, we investigate promising metal/TCO schemes, such as Ni/tin oxide (SnO2) and Ru/tin oxide (SnO2), for use in producing high quality ohmic contacts to p-GaN ($5x10^{17}cm^{-3}$). It is shown that both the contacts show linear current-voltage characteristics with increasing annealing temperature. Measurements show that specific contact resistances are in the range of $\sim 10^{-4}\Omega cm^2$ when annealed at 450-550°C in air ambient. The light transmittance of the contacts is shown to be comparable to other schemes reported at wavelengths in the range of 460 nm. Based on x-ray photoemission spectroscopy and Auger electron spectroscopy results, possible mechanisms for the formation of oxidized metals/TCO ohmic contacts are described and discussed.

Y5.45

Time Resolved Photoluminescence of Si-doped High Mole Fraction AlGaN Epilayers Grown by Plasma-Enhanced Molecular Beam Epitaxy. Madalina Furis[1], Alexander N. Cartwright[1], Jeonghyun Hwang[2] and William J. Schaff[2]; [1]Electrical Engineering, University of Buffalo, Buffalo, New York; [2]Electrical Engineering, Cornell University, Ithaca, New York.

Despite the significant progress made in the development of UV emitters, the fabrication of UV LEDs and laser diodes remains a challenging problem due, in part, to the difficulties encountered in the growth of high Al content AlGaN. Ultimately, AlGaN materials must be grown with reduced defect densities and high levels of both n- and p-type doping. Here, we report on detailed temperature dependent, time-resolved photoluminescence (PL) studies of Si-doped AlGaN epilayers. In these samples, the Al concentration varies from 25% to 66%. The samples were found to exhibit metallic-like temperature-independent conductivity. The deep level "yellow" emission, whose presence would indicate the existence of a large number of defects associated with growth, Si incorporation, and/or alloy formation, is absent. In addition to emission corresponding to the donor-bound exciton, the PL spectrum exhibits features associated with transitions involving localized carriers. This assignment of the emission mechanisms is based on the activation energies extracted from the temperature dependent photoluminescence quenching. Specifically, at room temperature the PL spectrum is dominated by transitions involving localized states. The localization energy varied from sample to sample and was observed to be between 110meV to 280meV. The excitonic PL decay time was 0.5ns at 15K and decreased to 0.1ns at room temperature. These measurements indicate that large electron concentrations can be achieved in high Al mole fraction AlGaN epilayers grown by plasma-enhanced molecular beam epitaxy without quenching of the band edge UV emission. These Si-doped AlGaN layers can be used as n-type contact layers as well as active layers in light emitting diode structures.

Y5.46

Effects of surface passivation in AlGaN/GaN heterostructure field effect transistor. Chang Min Jeon[1], Jae-Hoon Lee[2], Jung-Hee Lee[2], Mi-Ran Park[3], Kyu-Suk Lee[3] and Jong-Lam Lee[1]; [1]Materials Science and Engineering, POSTECH, Pohang, Gyeongbuk, South Korea; [2]Electronic and Electrical Engineering, Kyunpook National University, Daegu, Gyeongbuk, South Korea; [3]Electronics and Telecommunications Research Institute, Daejeon, Choong Nam, South Korea.

The AlGaN/GaN heterostructure field effect transistors (HFETs) have been considered to be one of the most promising candidates because of their potentially superior performance for high power and high frequency electronic devices. It has been reported that surface passivation with a dielectric such as amorphous silicon nitride can greatly reduce the amount of trapping in a HFET, resulting in significant improvement of available output power performances. These improvements could be due to the reduction of the traps, either bulk or surface, which cause loss of output power. However, the AlGaN/GaN heterostructure does make the devices sensitive to strain and the passivation layer of amorphous silicon nitride can affect the AlGaN layer with the strain. Thus, it is important to investigate the effect of surface passivation in AlGaN/GaN HFET in terms of traps for electrons and strain applied to the AlGaN layer by silicon nitride. However, no works has been conducted on the effect of strain in AlGaN/GaN HFET with surface passivation. The maximum drain current density (I_{max}) of AlGaN/GaN HFET was dramatically increased by 11.9 % after the passivation of 500 nm-thick-silicon nitride. In order to investigate the mechanism of effects in surface passivation, the stress measurement, deep level transaction spectroscopy (DLTS), and transconductance (g_m) dispersion were employed. The stress measurement shows that the curvature-radius of AlGaN layer on heterostructure decreased from 19.08 to 17.01 m corresponding to 12.17 %. It means that the tensile strain applied to the AlGaN increase and the 2 dimensional electron densities at the interface of AlGaN and GaN also increase due to the piezoelectric effect by the passivation. The surface trap densities for electrons decreased by the silicon nitride passivation. From these analyses, the effect of surface passivation in AlGaN/GaN HFET will be discussed

Y5.47

Anomalous composition dependence of optical energies of MBE-grown InGaN. Isabel Fernandez-Torrente[2], D. Amabile[2], R.W. Martin[2], K.P. O'Donnell[2], J.F.W. Mosselmans[1], E. Calleja[3] and F.B. Naranjo[3]; [1]Synchroton radiation Department, CLRC Daresbury Laboratories, Warrington, England, United Kingdom; [2]University of Strathclyde, Glasgow, Scotland, United Kingdom; [3]ETSI Telecomunicacion, Universidad Politecnica de Madrid, Madrid, Spain.

Two main methods are used for InxGa1-xN growth: high-temperature Metalorganic Chemical Vapour Deposition (MOCVD), proven to be successful for the growth of materials for commercial devices with low InN content (x<0.3), and low-temperature Molecular Beam Epitaxy (MBE), with better prospects for obtaining higher InN fractions (x>0.5). A direct comparison between MOCVD and MBE InGaN epilayers with similar InN concentration has been performed for the first time. The InN fraction in available MOCVD epilayers varies from 0 to 0.4 while in our MBE samples the range is 0.15-0.35. Wavelength Dispersive X-ray (WDX) analysis and Extended X-ray Absorption Fine Structure (EXAFS) spectroscopy were performed to determine the composition of the samples. In-situ cathodoluminescence (CL) and ex-situ photoluminescence (PL) energy mapping were combined with large-area optical absorption spectroscopy in order to assess the optical properties of the materials. The composition dependencies of the optical energies are found to vary with the growth method. The trendline of absorption bandgap and PL/CL peak energy versus InN fraction is linear in both cases. The energy obtained for zero InN concentration in MOCVD epilayers is close to the wurtzite-GaN bandgap of 3.4 eV at room temperature, while the equivalent figure for MBE samples is below 3.2 eV. We will attempt to explain this behaviour.

Y5.48

Anisotropic Dielectric Properties Of GaN Epilayers On Sapphire. Nelson Rowell, Guolin Yu and David Lockwood; National Research Council Canada, Ottawa, Ontario, Canada.

Polarized infrared reflectance from 300 to 1200 cm^{-1} at different incidence angles was measured for sapphire and GaN/sapphire samples. The approximately 1300 nm thick film of GaN was grown on c-plane sapphire by MOCVD without a buffer layer. Because of the hexagonal structure of sapphire and GaN, their uniaxial optical properties are anisotropic. In the p-polarized reflective spectrum, we can observe the mixed effect between the distinct infrared-active modes with dipole-moment oscillation perpendicular (E-mode) and parallel (A-mode) to the c axis. The contribution of the A-mode increased with increasing incidence angle. Therefore, we were able to obtain simultaneously the infrared dielectric functions parallel and perpendicular to the c axis, by fitting simultaneously three polarized reflectance spectra at three different incident angles with a suitable model. In the procedure, we adopted a new fitting technique, which we had proposed previously [1], i.e., fitting the first numerical derivative of the polarized reflectance spectra to improve the accuracy of the phonon parameters and to overcome the inconsistency between the model and measurement in the whole frequency range. Excellent agreement has been obtained between the measured and fitted first derivative reflectance spectra for both the sapphire and GaN/sapphire samples. The dielectric information thus obtained for sapphire and GaN are of greater accuracy than those reported previously. [1] G. Yu, N. L. Rowell, D. J. Lockwood and Z. R. Wasilewski; submitted to Applied Physics Letters.

Y5.49

Prism-Coupling Measurements of the Refractive Index and Birefringence of InGaN layers Grown on GaN films. Norman A Sanford[1], M R Krames[2] and A Munkholm[2]; [1]Optoelectronics Division, National Institute of Standards and Technology, Boulder, Colorado; [2]Lumileds Lighting, San Jose, California.

Prism-coupling methods combined with multilayer birefringent waveguide analysis were used to measure the ordinary and extraordinary indices of refraction of InxGa1-xN layers that were grown on GaN films. Sapphire (0001) was used as the substrate in MOCVD growth of all the InxGa1-xN/GaN structures examined.

Several samples were studied with x varying from 0 to 0.08. The In fraction was estimated using x-ray analysis and photoluminescence. Constraints imposed by strain limited the thickness range of a typical InxGa1-xN layer to approximately 300 nm. The thickness of a typical GaN layer was approximately 1300 nm. The measured mode effective indices of ordinary and extraordinary polarized waveguide modes launched into the InxGa1-xN/GaN films were used as input in least-squares solution procedures to solve for the film thickness, refractive index, and birefringence. Data were collected at several discrete wavelengths from 442 nm to 632 nm with the blue end of the measurement range limited by the optical absorption edge of the (rutile) prism. Results for samples with x > 0.08 will be presented at the meeting.

Y5.50
Intersubband Emissions in AlN/GaN Quantum Wells Probed by Photoluminescence. Mim L Nakarmi, Ki-Bum Nam, Neeraj Nepal, Jingyu Lin and Hongxing Jiang; Physics, Kansas State University, Manhattan, Kansas.

With a large band offset between AlN and GaN in the conduction band (about 1.9 eV) and a continuous variation of the band gap difference in AlGaN/GaN heterostructure, many important optoelectronic device applications based on AlGaN/GaN quantum wells (QWs) are conceivable. The success of conventional III-nitride devices such as edge-emitters and detectors based on the interband transitions are very encouraging for the study of new types of devices, such as QW light emitters and detectors based on intersubband transitions. The intersubband transitions in AlGaN/GaN QWs may be utilized for designing infrared (IR) detectors and emitters as well as quantum cascade (QC) lasers. The intersubband transitions reported so far in AlGaN/GaN QWs are absorption lines between different subbands in the conduction band. Light emission associated with intersubband transitions in AlGaN/GaN QWs has not been observed previously, although interband transitions involving different subbands in AlN/GaN QWs have been reported. One of the reasons could be that the growth conditions for AlN were not optimized. Recently, our group has achieved high optical quality AlN epilayers on sapphire substrates by metal-organic chemical vapor deposition (MOCVD). In this presentation, we report the epitaxial growth of AlN/GaN single quantum wells (SQW) by MOCVD by incorporating the established growth conditions of high quality AlN. Deep UV and IR time-resolved photoluminescence spectroscopy was employed to probe the intersubband transitions. For the first time, we have achieved III-nitride QWs in which light emission due to intersubband recombination is observable. For SQWs with a well width of about 2 nm, an intersubband emission peak at 1.302 eV, corresponding to the recombination of electrons between n = 2 and n = 1 sublevels, has been observed at 10 K. The recombination lifetime of the intersubband transition of electrons between n = 2 and n = 1 sublevels was measured and agrees well with the calculated radiative lifetime. By varying the well width, the transition wavelength for the intersubband transition can easily be tailored to the fiber optic communication wavelength. High quality AlN/GaN QWs that emit intersubband optical transitions form a basis for achieving novel III-nitride optoelectronic devices operating in the infrared wavelength range and considerably expand future prospects for the application of III-nitride materials.

Y5.51
Spectroscopy of the Intraband Electron Confinement in Self-Assembled GaN/AlN Quantum Dots. Ana Helman[1], Khalid Moumanis[1], Maria Tchernycheva[1], Alain Lusson[1], Francois Julien[1], Benjamin Damilano[2], Nicolas Grandjean[2], Jean Massies[2], Christophe Adelmann[3], Frederic Fossard[3], Daniel Le Si Dang[3] and Bruno Daudin[3]; [1]Action OptoGaN, Institut d'Electronique Fondamentale, UMR8622 CNRS, Universite Paris-Sud, Orsay, France; [2]CRHEA, UPR 10 CNRS, Valbonne, France; [3]CEA/CNRS Research Group "Nanophysique et Semiconducteurs", DRFMC/SPMM, CEA/Grenoble, Grenoble, France.

We report on the first observation of conduction-band interlevel transitions at room-temperature in self-organized GaN/AlN quantum dots (QD) grown by molecular beam epitaxy (MBE) on sapphire, silicon (111) and 6H-SiC substrates [1]. Based on transmission electron microscopy (TEM) and AFM measurements, the dots form as truncated pyramids with a hexagonal base with a diameter to height ratio of 5 and a dot density of 1-3x10^{11} cm^{-2}. Quantum dot superlattices with 1.6 nm (6.7 nm) deposited GaN (AlN) layers have been investigated using photoluminescence (PL). The 300 K PL under excitation at 244 nm of the wetting layer (WL) absorption is peaked at 3.0 eV (2.97 eV) for the QDs grown on silicon (sapphire) substrate. The full width at half maximum (FWHM) is ~0.6 eV for both samples reflecting the size dispersion enhanced by the quantum confined Stark effect due to internal field. A strong reduction of the PL linewidth is observed by exciting carriers directly in the QDs, i.e. at the energy below the WL absorption edge. By resonant excitation at 351nm the PL energy and FWHM are 3.0 eV (2.93eV) and 0.19 eV (0.37 eV), respectively for the sample grown on silicon (sapphire). The PL shifts to low energy when decreasing excitation photon energy, which confirms a dot-size selective population mechanism. Under 351 nm excitation, we estimate the height of the selected dots to be 4 nm (4.5 nm) for the QDs grown on silicon (sapphire) substrate. The electron confinement in the QD superlattices has been investigated at 300 K using photo-induced absorption spectroscopy. Under 351 nm excitation, a strong in-plane polarized absorption is observed at 0.15 eV. We claim that this absorption related to the QD in-plane confinement arises from the electron s-p_x resonance. At higher energy, three absorption resonances with a polarization component along the growth axis are also observed respectively peaked at 0.59 eV (0.53 eV), 0.85 eV (0.73 eV) and 0.97 eV (0.98 eV) for the sample grown on silicon (sapphire) substrate. Based on an effective-mass modeling of the electron confinement along the growth axis, i.e. neglecting the in-plane confinement but accounting for the internal field, we attribute the resonances at 0.5-0.6 eV and around 1 eV respectively to the s-p_z and s-d_z interlevel absorptions. The oscillator strength associated with the s-d_z transition is calculated to be 8 times smaller than that associated with the s-pz transition, which is in agreement with experiments. Based on the s-p_x and s-p_z transition energies, we attribute the resonance around 0.8 eV to the s-p_x-p_z interlevel absorption. We also show that the magnitude of the internal field in these rather big dots is the main parameter governing the interlevel transition energies in the range 0.5-1eV. New results on QDs of various sizes grown on sapphire, 6H-SiC or silicon basically confirm the above interpretations. [1] K. Moumanis et al., Appl. Phys. Lett. 82, 868 (2003) ; Physica E 17, 60 (2003)

Y5.52
Optical Properties of N- AND Ga-Polarity GaN. Abigail Bell[1], J L Smit[1], F A Ponce[1], Hock M Ng[2], Aref Chowdhury[2] and Nils G Weimann[2]; [1]Physics and Astronomy, Arizona State University, Tempe, Arizona; [2]Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey.

A GaN sample with adjacent Ga- (0001) and N-polarity (000$\bar{1}$) regions was studied by cathodoluminescence (CL). The sample was grown by plasma-assisted MBE on a sapphire substrate with a 20nm to 30nm AlN buffer layer. A thin layer of GaN (~100 nm) was deposited on the buffer layer to prevent any oxidation of the AlN layer upon removal from the growth chamber. The sample was lithographically patterned with photoresist to cover parts of the GaN/AlN layers and was etched until the sapphire substrate was exposed. This resulted in a sample with ~8 micron stripes of exposed sapphire between ~8 micron stripes with an AlN buffer layer. The sample was placed back into the growth chamber and further growth of undoped GaN was initiated resulting in regions of Ga- and N-polar material. The Ga-polarity material was grown on the buffer layer and the N-polarity material was grown directly on the sapphire substrate. SEM revealed that the Ga-polarity regions have a smooth surface while the N-polarity regions are rough. The N-polarity regions were found to etch under 2M KOH solution revealing pyramids {10-1-1} faces. The Ga-polarity regions do not etch. Spatially resolved CL measurements were performed at room temperature to characterize the differences in the optical properties for the two polarities. The near band-edge emission from the N-polarity emission is at least one order of magnitude brighter than the Ga-polarity material. The Ga-polarity material exhibits near band-edge emission at 363nm, whereas the near band-edge emission from the N-polarity regions has a double peak at 363nm and 369nm. CL spectra were taken in spot mode on different facets of the N-polarity pyramids and the intensity of the 369nm emission varies from facet to facet. In addition, the N-polarity material exhibits a broad blue emission at 430nm. The 430nm emission appears to emanate from both the pyramidal features and the bulk of the N-polarity material. No yellow luminescence is observed in either region. We investigate the origin of 430nm emission in the N-polarity material.

Y5.53
Photoluminescence from Freestanding GaN with (10-10) Orientation. Michael A. Reshchikov[1], Ali Teke[1], Herbert-Paul Maruska[2], David W. Hill[2] and Hadis Morkoc[1]; [1]Electrical Engineering, VCU, Richmond, Virginia; [2]Crystal Photonics, Inc., Sanford, Florida.

Large free-standing GaN wafers will be valuable substrates for homoepitaxial growth of advanced nitride-based devices. In this vein, we have prepared 50 mm diameter GaN films each about 300 microns thick on nearly lattice-matched $LiAlO_2$ substrates using halide vapor phase epitaxy (HVPE). Using GaCl and NH3 as precursors, growth is performed at 875C in a three-zone tube furnace. After removal of the $LiAlO_2$ substrate, the free-standing GaN wafers are found to have the non-polar (10-10) orientation. The wafers were cut, mechanically polished from both sides, and cleaned in HCl. Photoluminescence (PL) spectrum from both sides is dominated by two peaks at 3.47 and

3.43 eV, preliminarily attributed to an exciton bound to the neutral shallow donor and unidentified structural defect, respectively. The quantum efficiency of the exciton-related emission exceeds 10%, whereas that of the combined emission from the defect-related bands (red, yellow and blue) is below 0.1%. Evolution of the PL spectrum with temperature and excitation intensity is analyzed in detail. Effects of polishing and etching on the PL properties and surface morphology will be also discussed.

Y5.54

Carrier Dynamics of Monolithic InGaN/GaN Light-Emitting PN-Junction Structures with Two Active Regions. Yun-Li Li[1], J. M. Shah[1], Th. Gessmann[1], E. F. Schubert[1] and J. K. Sheu[2]; [1]Electrical, Computer, and System Engineering Department, Rensselaer Polytechnic Institute, Troy, Massachusetts; [2]Optical Science Center, National Central University, Chung-Li, Taiwan.

The most energy-efficient way to generate white light is the mixing of two narrow emission lines, namely one in the blue and one in the yellow-green region of the visible spectrum. Efficient monolithic solid-state white light sources can be demonstrated by using quantum well structures emitting at two wavelengths. In this work, monolithic InGaN/GaN light-emitting pn-junction structures with two active regions grown by metal-organic chemical vapor deposition are investigated. In addition, the carrier dynamics of such quantum well structures is analyzed. Room-temperature and low-temperature photoluminescence and room-temperature electroluminescence measurements show two emission bands originating from the two active regions. We find markedly different emission characteristics for photo-pumped and current-injected excitation. In photo-pumped experiments, the intensity ratio depends strongly on the excitation level whereas for current-injection, a constant intensity ratio is found. The independence of spectral shape on the injection current is a favorable property as it results in an emission color independent of the injection current density. The dependency of the emission on excitation is discussed and attributed to carrier transport between the two active regions and to the different carrier injection dynamics in photoluminescence and electroluminescence. The theoretical luminous efficacy of a gaussian dichromatic white-light source is calculated assuming a line broadening ranging from 2 kT to 10 kT. Luminous efficacies ranging from 380 to 440 lm/W can potentially be obtained for broadened dichromatic sources, illustrating that very high luminous efficacies could be reached with dichromatic light-emitting diodes.

Y5.55

Structural Defect-Related Photoluminescence in GaN. B J Skromme[1], L. Chen[1], M. K. Mikhov[1], H. Yamane[2], M. Aoki[2], F. J. DiSalvo[3], B. Wagner[4], R. F. Davis[4], P. A. Grudowski[5] and R. D. Dupuis[5]; [1]Department of Electrical Engineering and Center for Solid State Electronics Research, Arizona State University, Tempe, Arizona; [2]Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, Aoba-ku, Sendai, Japan; [3]Department of Chemistry and Chemical Biology, Cornell University, Ithaca, New York; [4]Department of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; [5]Microelectronics Research Center, University of Texas, Austin, Texas.

Broad, low temperature photoluminescence (PL) peaks near 3.4-3.42 eV in GaN have previously been associated with structural defects and in particular basal-plane stacking faults, based on empirical correlations with transmission electron microscopy. Recently, we have observed unusually sharp and highly structured PL peaks in this region in high quality bulk GaN grown from a Na/Ga flux, some of which display characteristic shifts and narrowing as a function of excitation power. Here, we study the behavior of these peaks as a function of excitation intensity, temperature, and crystal polarity, and compare them to those observed in GaN grown on off-axis SiC or sapphire substrates by metalorganic chemical vapor deposition (MOCVD). In the off-axis material on either substrate, similar peaks are observed to those in the bulk samples, but also a low energy peak near 3.21 eV that does not occur in the bulk material. This peak is not the donor-acceptor pair band of wurtzite material, as it was assigned in previous work, but is most probably related to another structural defect. The peaks in the off-axis material do not generally show the shifts with excitation power observed in the bulk samples. We describe a preliminary model for these features based on spatially indirect recombination involving 3C quantum wells embedded in the 2H matrix. Band bending is present due to the spontaneous polarization in the 2H phase, which is absent in the 3C layers. The laser excitation flattens the bands to some degree, producing the observed shifts.

Y5.56

Room Temperature Time-Resolved Photoluminescence Studies of AlGaN on GaN Templates. Gregory A. Garrett, A V Sampath, C J Collins, H Shen and M Wraback; Sensors and Electron Devices Directorate, US Army Research Lab, Adelphi, Maryland.

Optical characterization of $Al_xGa_{1-x}N$ with different Al concentrations was undertaken to investigate the importance of deep defect-related states and alloy fluctuations on the photoluminescence lifetime and the subsequent suitability of these materials for ultraviolet light emitting devices. Sub-picosecond time-resolved photoluminescence (TRPL) was acquired using a recently developed technique of gated *down*-conversion in a non-linear optical crystal. This temporal resolution allowed for the measurement of TRPL from AlGaN alloys at room temperature where fast, non-radiative decay channels are expected to dominate. The material studied was grown by RF-plasma-assisted molecular beam epitaxy on thick hydride vapor phase epitaxy GaN templates. Observations of nominally x=0.10 and x=0.20 Al content epilayers, show room temperature lifetimes of ~150 ps. These half-life measurements are consistent with the TRPL signals of the GaN templates, which had estimated defect densities in the mid 10^8-10^9 cm^{-2} range, and are better than values found for AlGaN on sapphire (less than 20 ps), with presumably higher defect densities. This suggests that the bandtail states are shallow enough that the carriers are thermally activated such that the TRPL decays are dominated by trapping in deep defect states. By comparison, measurements of a nominally x=0.40 Al content epilayer showed degradation of the lifetime to ~75 ps. Moreover, at lower excitation densities, the lifetime became significantly faster (~25 ps), indicating the presence of a saturation effect not as evident in the lower concentration samples. This behavior implies that the carriers are trapped in bandtails with activation energy larger than kT, and are funneled through those states to the deep defect levels. Also, the intensity dependence implies that it is this decay path through the bandtail states that saturates, which in turn shows the emergence of alloy fluctuation as a significant contributor to the carrier dynamics and optical properties of higher Al concentration material.

Y5.57

Ultrafast Carrier Dynamics in MBE Grown InN Epilayers. Fei Chen[1], Alexander N Cartwright[1], Hai Lu[2] and William J Schaff[2]; [1]Department of Electrical Engineering, University at Buffalo, State University of New York, Buffalo, New York; [2]Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York.

Ultrafast two-color differential transmission measurements on a series of InN epilayers, with varying free electron concentrations, grown by molecular beam epitaxy have been employed to probe the carrier recombination dynamics and hot carrier relaxation processes in these materials at room temperature. These measurements were performed with a pump energy of 1.55 eV and probe energies varying from 0.6 eV to 1.0 eV. The peak energy of the change in absorption was consistent with the 0.7 eV bandedge recently reported in these materials. Moreover, we observed a fast initial hot carrier cooling to the lattice temperature followed by a slower recombination process after pulsed excitation. At short time delays, modeling of the observed relaxation suggests that the dominant energy relaxation process is longitudinal optical phonon scattering modified by a strong hot phonon effect. At longer times, a redshift of the peak energy in the differential transmission spectra was observed. This redshift is consistent with a reduction of the bandfilling effects that occurs as the photoexcited carriers recombine. Furthermore, our results demonstrated that the room temperature carrier lifetimes in these materials are inversely proportional to the free electron concentrations. This suggests that the donor-like defects or impurities may stimulate a formation of non-radiative recombination centers reducing the carrier lifetime. More importantly, carrier lifetimes as long as 1.3 ns were observed, indicating high crystalline quality. Thus, the observed long carrier lifetime and strong photoluminescence at room temperature make these InN crystals excellent candidates for the infrared emitters.

Y5.58

Magneto-luminescence from a two-dimensional electron gas in undoped AlGaN/GaN heterostructures. Gema Martinez-Criado[1,2], Andres Cantarero[2], Jose Manuel Calleja[3], Angela Link[4], Oliver Ambacher[5] and Martin Stutzmann[4]; [1]ID22: Micro-Fluorescence/Imaging/Diffraction Group, European Synchrotron Radiation Facility (ESRF), Grenoble, France; [2]Materials Science Institute, University of Valencia, Burjasot; [3]Dpto. Fisica de Materiales, Universidad Autonoma de Madrid, Cantoblanco, Madrid, Spain; [4]Walter Schottky Institute, Technical University of Munich, Garching, Munich, Germany; [5]Center for Micro-nanotechnologies, Technical University of Ilmenau, Ilmenau, Ilmenau, Germany.

The radiative recombination in undoped AlGaN/GaN single heterostructures was studied by magneto-photoluminescence measurements at low temperatures. Spontaneous and piezoelectric polarization effects induce a high electron accumulation at the heterointerface. The resulting two-dimensional electron gas has been clearly revealed by Shubnikov-de Haas oscillations in the longitudinal magneto-resistance above 5 T. On the other hand, photoluminescence spectra measured in magnetic fields up to 12 T show well-defined

peaks involving the two-dimensional electron gas. These pronounced bands are energetically located below the typical bound and free excitonic lines. A clear magneto-oscillatory behavior in their intensity, photon energy and peak width was found as a function of the magnetic field. In terms of population effects and many-body interactions, these magneto-optical oscillations are analyzed.

Y5.59
Optical and microstructural evaluation of pretreated InGaN quantum well structures. Tim Boettcher[1], Angelika Vennemann[1], Frank Bertram[2], Peder Bergman[3], Akio Ueta[1], Rosa Chierchia[1], Roland Kroeger[1], Juergen Christen[2] and Detlef Hommel[1]; [1]Inst. of Solid State Physics, University of Bremen, Bremen, Germany; [2]Inst. of Experimental Physics, University of Magdeburg, Magdeburg, Germany; [3]Department of Physics and Measurement Technology, Linkoeping University, Linkoeping, Sweden.

In order to optimize the quantum efficiency of InGaN quantum wells for visible light emitting devices, different MOVPE growth sequences are compared in view of microstructure and luminescence. In particular, the pretreatment of the surface prior to the well deposition utilizing silicon and indium was studied in order to raise the photoluminescence (PL) efficiency at room temperature [1,2]. In both cases, the luminescence efficiency is strongly enhanced, while at low temperature the differences (4K) are only minor. Neither the well thickness nor the average composition are affected significantly, which is demonstrated by X-ray reflectivity and X-ray diffraction measurements. For the case of Si pretreatment, the generation of localized charges at the lower interface appears to screen the piezoelectric field quite efficiently. In addition, it seems to affect the microstructure, since histograms of cathodoluminescence (CL) mappings taken at low temperature show, that the distribution of the local emission peaks is broadened upon Si deposition. Just the opposite is the case for the pretreatment utilizing indium. In this case the wavelength distribution in the CL is narrowed, which can be attributed to more homogeneous quantum wells. A reason for this could be a reduction of the indium surface segregation due to the pre-wetted surface. The microstructure of the quantum wells is evaluated utilizing high-resolution transmission electron microscopy and the digital analysis of lattice images (DALI) technique, taking the electron-beam induced degradation into account. The findings are in agreement with numerical bandstructure simulations and will be discussed on the basis of time-resolved PL measurements. [1] Keller et al., J. Cryst. Growth 195, 258 (1998) [2] Zhang et al. Appl. Phys. Lett. 80, 485 (2002)

Y5.60
Strain evolution and phonons in AlN/GaN superlattices. V. Darakchieva[1], P. P. Paskov[1], M. Schubert[2], T. Paskova[1], E. Valcheva[1], A. Kasic[1], H. Arwin[1], B. Monemar[1], H. Amano[3] and I. Akasaki[3]; [1]IFM, Linkoping University, Linkoping, Sweden; [2]Leipzig University, Leipzig; [3]Meijo University, Nagoya, Japan.

AlN/GaN and AlGaN/GaN superlattices (SLs) have been subject of intense investigation due to their potential applications for high power transistors and ultraviolet laser diodes. However, only a few reports are devoted to their vibrational properties. The formation of SL induces a folding of the Brillouin zone in the growth direction leading to the appearance of new phonon modes. In addition, the SL constituents are under strain resulting in strain-induced shift of the SL phonon frequencies, which further complicate the mode identification. In this work we report on the strain evolution and vibrational properties of AlN/GaN SLs grown by metalorganic vapor phase epitaxy on (0001) sapphire substrates using GaN buffer layer. The structures consist of 10 period SLs with different well thickness, keeping the well-barrier thickness ratio as 3:1. The SLs were studied by infrared spectroscopic ellipsometry (IRSE) and reciprocal space mapping (RSM). The 10-14 RSM of the short-period SL show that the SL is grown coherently on the GaN layer and both the barrier and the well have the same in-plane lattice parameter as the underlying GaN layer. In other words there is a large tensile strain in the AlN layers and a small compressive strain in the GaN wells. The latter is manifested by a small shift of 2 cm-1 of the GaN E1(TO) frequency from the strain-free position. It is found that with increasing the SL period the AlN barrier layers start to relax, which is reflected by the increase of the AlN E1(TO) frequency towards the strain-free value. Accordingly, the compressive strain in the GaN well layers increases evidenced by the blue-shift of the GaN E1(TO) mode. In addition to the GaN and AlN bulk phonos, two other modes are identified in the IRSE spectra of all samples and are suggested to originate from the Brillouin zone folding.

Y5.61
Effects of Biaxial Strain on the Formation of Ordered Phases in Cubic InGaN. J. R. Leite, L. K. Teles, L. G. Ferreira and L. M.R. Scolfaro; Materials Science, University of Sao Paulo, Sao Paulo, SP, Brazil.

Considerable effort has been devoted in recent years to the study of structural and optical properties of hexagonal and cubic InGaN epitaxial layers. The motivation behind these investigations is the fact that the InGaN ternary alloy is the active medium in the highly efficient quantum-well structure light-emitting diodes and laser diodes operating in the short-wavelength visible and UV regions of the spectrum. Despite these important applications, the light emission process of the devices is still a matter of controversy in the literature. There is strong evidence that an important emission mechanism originates from phase-separated quantum dots (QDs) formed by alloy decomposition taking place in the InGaN layer. It has been recognized that the phase separation can be suppressed due to biaxial strain in coherently grown epitaxial layers. It is also well known that the biaxial strain can be a driving force for ordering formation. Moreover, chemical ordering on the group-III sublattice of InGaN has also been reported. It is already known for various III-V semiconductors that long-range, or short-range, ordered stoichiometric inter-semiconductor compounds can be more stable than the disordered alloy below a certain growth temperature. Therefore, a deep understanding of the role played by strain on phase separation and ordering formation in InGaN layers is highly desirable. The control of strain parameters is important to monitor the QDs formation in the active region of the devices. We present a rigorous theoretical study of the effects of biaxial strain on the ordered phases formation in cubic InGaN alloys. The calculations performed here are based on an ab initio pseudopotential plane-wave method, within the framework of the density functional theory and the local density approximation, and a cluster expansion method together with Monte Carlo simulations. We compare our results with data obtained from high-resolution x-ray diffraction and micro-Raman spectroscopy measurements.

Y5.62
Parameters of acousto-optic interaction in AlGaN layers on sapphire and AlN substrates. D. Ciplys[1,4], Michael Shur[1], Gang Bu[1], Remis Gaska[2], Qhalid Fareed[2], L. J. Schowalter[3] and R. Rimeika[4]; [1]Department of ECSE and Broadband Center, Rensselaer Polytechnic Institute, Troy, New York; [2]Sensor Electronic Technology, Inc., Columbia, South Carolina; [3]Crystal IS, Inc, Latham, New York; [4]Department of Radiophysics, Vilnius University, Vilnius, Lithuania.

Surface acoustic waves (SAW), guided optical waves (GOW) in nitride films and their interaction have attracted a great deal of attention because of their potential applications for acoustooptic devices operating in blue and ultraviolet regions. We present the results of our investigations of the acoustooptic interaction between SAWs and GOWs in AlGaN layers grown by MOCVD on sapphire and bulk AlN substrates. We present the analysis of the layer and substrate properties corresponding to optimum conditions of the acoustooptic interaction. A large difference between the layer and substrate refractive indices for the AlGaN on sapphire optical waveguides causes multimode regimes of operation for typical layer thicknesses on the order of microns. In contrast, the single mode optical waveguiding can be easily achieved in the structures consisting of AlGaN layers grown on bulk AlN due to the close values of the layer and substrate refractive indexes. Also, the efficiency of the SAW excitation in such structures is considerably enhanced due to piezoelectric properties of the substrate.

Y5.63
X-Ray Diffraction and Raman Studies of Relaxation of Residual Elastic Strain in GaN Epitaxial Layers Grown by HVPE on SiC(0001) Substrate. Nikolai N Faleev[1], I. Ahmad[2], Mark Holtz[2], Henryk Temkin[3] and Yuri Melnik[4]; [1]XRD, Rigaku/MSC, Inc., The Woodlands, Texas; [2]Physics, Texas Tech University, Lubbock, Texas; [3]Electrical Engineering, Texas Tech University, Lubbock, Texas; [4]TDI, Inc., Gaithersburg, Maryland.

Gallium nitride and related compound semiconductors are one of the most attractive wide-band-gap materials for optical device applications. Recent progress in growth procedures (MOCVD, MBE, HVPE, et al.) has greatly improved crystalline perfection of nitride materials. Nevertheless crystalline perfection of III-V nitride heterostructures is still one of the most serious problems for further improvement of devices. Therefore investigations addressing the relationships between epitaxial growth conditions and defect generation in these materials are still urgent. We report detailed studies of GaN/SiC(0001) epitaxial structures using high resolution x-ray diffraction and Raman spectroscopy. Samples were grown by HVPE under the same conditions directly on SiC substrates without an AlN buffer layer. The thickness of GaN layers ranged from 300 nm up to 40 mkm. The initial thin (~25 nm) GaN growth layer used in order to accommodate mismatch of lattice parameters between substrate and epitaxial structures. Preliminary results [A.Kazimirov, N.Faleev, H.Temkin et al., J.Appl.Phys.,80, 6092, (2001)] revealed that thin (300 nm) epitaxial layer has unusually high crystalline perfection. Density of dislocations in the layer is less than 2-3 x

$10^7/cm^4$; roughness of surface is about 30 nm, and lateral coherence length exceeds 0.6 mkm. Our recent data reveals that in the ~ 25 nm thick initial layer denoted Region I, the initial lattice misumtch between the substrate and epilayer is nearly completely (about 92-94%) accommodated. Region I thus provide a transition to the homo-epitaxial growth mode seen in Region II. The residual tensile elastic strains in Region II are maximum in thin (around 0.4 - 0.6μm) epitaxial layers, ranging from $2.0 \times 10^{-3}$to 3.5×10^{-3}. These strains are more than one order of magnitude smaller than in Region I, and agree with what we estimate from differences in the thermal expansion coefficients between GaN and SiC substrate. The transition to homo-epitaxy results in diminishes of density of dislocations in Region II of the epitaxial layer (down to $1\text{-}2 \times 10^7/cm^2$). For layers with thickness exceeding 0.6 mkm we observe Region III for which there is a gradual reduction in strain with increasing thickness. The strain diminishes one order of magnitude and density of dislocations increases (up to $6\text{-}8 \times 10^8/cm^2$) by thickness ~ 9-10 mkm. We discuss our results, along with those of other groups, showing that these regions are present in the initial stage of homoepitaxial growth under various methods and in other III-Nitride compounds. In order to explain these observations, a model for the processes of growth, relaxation of elastic strain and defect generation is proposed. In this model the main factors considered are lattice mismatch and elastic strains, stoichiometry during the growth process, and gettering of point defects by dislocations.

Y5.64

Confocal Photoluminescence and Cathodoluminescence Studies of AlGaN. Volkmar R Dierolf[1], O. Svitelskiy[1], G. S. Cargill[2], A.Y. Nikiforov[2], J.D Acord[3] and J.M. Redwing[3]; [1]Physics, Lehigh University, Bethlehem, Pennsylvania; [2]Materials Science & Engin., Lehigh University, Bethlehem, Pennsylvania; [3]Materials Science & Engin., Pennsylvannia State University, University Park, Pennsylvania.

Development of UV lasers and LEDs is currently the main driving force for investigating the optical properties of AlGaN. One of the avenues to achieve high luminescence quantum efficiencies (even in the presence of rather high defect concentrations) is the localization of excitation by composition fluctuations. For that purpose we studied a variety of samples grown by MOCVD, using spatially resolved confocal photoluminescence spectroscopy. In this technique, we record large numbers of PL spectra at low temperatures (T=4K) while scanning over the samples in small steps. A detailed evaluation of the spectra in terms of total intensity, emission peak positions and spectral line width gives us high sensitivity to composition fluctuations on the 1 μm length scale. For instance, we are able to determine Al_x/Ga_{x-1} fluctuations smaller than $\Delta x/x=2x10^{-3}$. In our samples with an average Al content of x = 10% we find islands about 2 μm in size, in which the emission energy for the D^0X exciton is shifted considerably (0.5nm) compared to the rest of the sample. This corresponds to a variation $\Delta x/x=2x10^{-2}$. For these islands, the emission intensity is increased by about 30%. In contrast to this, much smaller changes are observed in the emission from other impurity related excitons, which appear about 150meV shifted to lower energies. These observations may be first indicators that composition fluctuations are occurring. Currently we are investigating the dependence of the fluctuations on growth conditions, Al/Ga ratio, substrate type (sapphire vs. SiC) and residual film stress. Moreover, we are performing cathodoluminescence measurements and are correlating the results with PL and with the accurate average composition determined by SIMS. Results and conclusions from these on-going studies will be reported.

Y5.65

Threading dislocation evolution in GaN epitaxial layers by in situ patterning ELOG. Xiaolong Fang, Daewoo Kim, Manu Rao and Subhash Mahajan; Chemical and Materials Eng., Arizona State University, Tempe, Arizona.

By direct deposition of a very thin silicon nitride layer on an as-grown GaN nucleation layer (NL), we achieved in situ patterning ELOG mode for the growth of high temperature (HT) GaN layer. The patterning was produced by HT annealing, which made NL islands protrude through silicon nitride layer and form outcroppings. Initial HT-GaN nucleated on these outcroppings and laterally grew over the silicon nitride layer. Threading dislocation (TD) density was reduced by about two orders of magnitude, as compared to the conventional two-step growth technique. Wing twist and tilt problems in ex situ ELOG were avoided due to smaller window separation and much earlier coalescence. The in situ patterning made the ELOG technique much simpler. A series of early stage overgrowths of HT-GaN by in situ patterning ELOG were examined to understand the mechanism of TD reduction using TEM and AFM. The initial HT-GaN island density was reduced compared to two-step growth technique, so the vertical growth rate was relatively high. After 4 minutes the island height reached 300nm to 400nm, while the average overgrowth rate should be around 28nm/min. The overlayer was continuous with a very smooth surface at approximately 500nm after 20 minutes growth. Inside islands, TDs propagate from the NL at periodically distributed growth sites. Although stress contrast appears in the coalescence front between two islands, no TDs were observed in this region. TD bending towards the facets of islands occurred only before coalescence. Very small voids existed near the bottom of HT-GaN associated with vertical dislocations. However, no horizontal dislocations were presented in late grown HT-GaN. The support of our work by AFOSR is greatly acknowledged.

Y5.66

Manifestation of Structural Defects in Photoluminescence from GaN. Michael A. Reshchikov[1], Feng Yun[1], Jacek Jasinski[2], Zuzanna Liliental-Weber[2] and Hadis Morkoc[1]; [1]Electrical Engineering, VCU, Richmond, Virginia; [2]LBNL, Berkeley, California.

A series of sharp intense peaks is sometimes observed in the low-temperature photoluminescence (PL) spectrum of unintentionally doped GaN in the photon energy range between 3.0 and 3.46 eV that are attributed to excitons bound to yet unidentified structural and surface defects. These *unusual* peaks are named Y lines due to the similarity of their properties to those of the Y lines in II-VI compounds. Most of these peaks (at 3.21, 3.32, 3.34, 3.35, 3.38, and 3.42 eV) are typically observed in Ga-polar films. We analyzed X-ray diffraction data in a large set of GaN samples grown by molecular beam epitaxy in order to find any correlation between these unusual PL peaks and the GaN crystal structure. Moreover, in selected samples exhibiting strong Y peaks, cross-sectional transmission electron microscopy (TEM) was taken in an effort to detect the presence and density of various structural defects. The preliminarily results indicate that at least some of the Y lines in GaN are not directly related to the observed structural defects, such as edge, screw, or mixed dislocations. However, there exists the possibility that point defects trapped at dislocations are responsible for these PL peaks.

Y5.67

Raman Characterization of Strained GaN_yAs_{1-y} and $In_xGa_{1-x}N_yAs_{1-y}$ Epilayers. Li-Lin Tay, D.J. Lockwood, J.A. Gupta and Z.R. Wasilewski; Institute for Microstructural Sciences, National Research Council, Ottawa, Ontario, Canada.

Pseudomorphically strained epitaxial films of the ternary alloy GaN_yAs_{1-y} have been grown on GaAs(100) with y ranging from 0 to 0.05. Samples of GaN_yAs_{1-y} about 35 nm thick were grown both without and with a 5 nm GaAs cap. Raman studies in quasibackscattering geometry were performed on both capped and uncapped alloys. The phonon Raman spectrum displays a two-mode like behavior. The GaAs-like first order Raman modes are represented at y=0.05 by the strong longitudinal optic (LO) mode at 288.7 cm^{-1} and the weaker transverse optic (TO) mode at 268.4 cm^{-1}. The GaN-like LO phonon vibrational mode is observed for y=0.05 at 471.9 cm^{-1}. The alloying effect is also observed through two very broad disorder-induced acoustic bands at ~80 and ~170 cm^{-1} indicating obvious atomic disorder within the crystalline network. Raman studies show that as the nitrogen concentration increases, the GaAs-like LO band shifts towards lower wavenumber from 290.8 cm^{-1} at y=0 to 288.7 cm^{-1} at y=0.05. In addition, the GaN-like phonon band showed a proportional increase in its intensity and its frequency as the concentration of nitrogen increases. Second order GaAs-like Raman vibrational bands were also observed at 509, 534 and 570 cm^{-1} for y=0.05. The Raman shift and strain level, as characterized by x-ray diffraction, will be correlated for the GaN_yAs_{1-y} samples. Raman results for the unstrained quarternary alloy $In_{0.06}Ga_{0.94}N_{0.02}As_{0.98}$ on GaAs(100) will also be presented.

Y5.68

Optical study of localized and delocalized states in GaAsN/GaAs. Zhongying Xu[1], Xiangdong Luo[1] and Weikun Ge[2]; [1]NLSM, Institute of semiconductors, CAS, Beijing, China; [2]Dept. of Physics, HongKong University of Science and Technology, HongKong, China.

GaAsN semiconductor alloys grown on GaAs substrate have attracted much attention due to their unusual physical properties and potential applications in long wavelength optoelectronic and photonic devices. Understanding the emission mechanism in these materials is very important, not only from the viewpoint of physical interest but also for the device design. In recent optical studies, the strong action of N atoms in GaAs and the large strain between GaAsN and GaAs have been shown to make the absorption and photoluminescence (PL) very complicated. In PL measurements, N-related pair states, cluster states, localized band-tail states and delocalized states were reported in various experiments. In this work, we use various optical techniques to study exciton localization and delocalization effects in GaAsN/GaAs system. The main results are: 1. Under short pulse laser excitation, we have observed a new PL emission from GaAsN/GaAs single quantum wells (QWs). It dominates the PL spectra under high

excitation and/or at high temperature. By measuring the PL dependence on both temperature and excitation power and by analyzing the time-resolved PL results, we have attributed the new PL peak to the recombination of delocalized excitons in QWs. Furthermore, a competition process between localized and delocalized excitons is observed in the temperature-dependent PL spectra under the short pulse excitation. This competition is believed to be responsible for the temperature-induced S-shaped PL shift often observed in the disordered alloy semiconductor system under continuous wave (cw) excitation. 2. We have investigated a set of GaAs1-xNx samples with small nitrogen composition (x<1%) by cw-PL, pulse-wave (pw) excitation PL, and time-resolved PL. In the PL spectra, an extra transition located at the higher-energy side of the commonly reported N-related emissions was observed. By measuring the PL dependence on temperature and excitation power, the new PL peak was identified as a transition of alloy bandedge-related recombination in GaAsN. The PL dynamics further confirms its intrinsic nature as being associated with the bandedge rather than N-related bound states. 3. We have used selective excitation PL to further explore the emission properties of GaAsN/GaAs SQWs. A significant difference is observed in the PL spectra when the excitation energy is set below or above the band gap of GaAs. By comparing the experimental results of the bulk GaAsN, the observed difference in QWs was attributed to the exciton localization effect at the GaAsN/GaAs interface. This interface-related exciton localization effect can be greatly reduced by a rapid thermal annealing process.

Y5.69
Strong dependence of the fundamental band gap on the alloy composition in cubic InxGa1-xN and InxAl1-xN alloys.
Zoulikha Dridi[1,2], Bachir Bouhafs[1,2] and Pierre Ruterana[1]; [1]LERMAT, ENSICAEN, CAEN, France; [2]LSMSM, Departement de Physique, Faculte des Sciences, Universite de Sidi-Bel-Abbes, Sidi Bel Abbes, Algeria.

Ab initio total energy calculations, based on the full-potential augmented plane wave method within the local density approximation, are used to study the influence of alloying on the structural and electronic properties of cubic InxGa1-xN and InxAl1-xN ordered alloys in the chalcopyrite and luzonite structures. We have investigated the lattice parameters and band gap energies. The lattice parameters, exhibit an upward bowing of -0.05 A and -0.15 A, respectively for the InxGa1-xN and InxAl1-xN alloys. The composition dependence of the band gap is found to exhibit a relatively small bowing parameter of 1.36 eV for InxGa1-xN. The band gap versus composition plot for InxAl1-xN alloys is well fit with a large bowing parameter of 3.19 eV, and presents a direct to indirect band gap crossover at x (Al) = 0.83. The large bowing effect in InxAl1-xN alloys has been discussed in terms of a composition dependent bowing parameter.

Y5.70
Structural, energy gap, and thermodynamic properties of AlxGayIn1-x-yN quaternary alloys.
L. M.R. Scolfaro, M. Marques, L. K. Teles, L. G. Ferreira and J. R. Leite; Materials Science, University of Sao Paulo, Sao Paulo, SP, Brazil.

The group-III nitride semiconductors and their ternary alloys have been extensively investigated due to their importance for the electronic and opto-electronic device technology. Recent examples are the opto-electronic commercial devices operating in the green-blue-UV spectral region. By alloying among the group-III nitrides one can vary the band-gap from ~0.7-0.9 eV (InN) till ~6.3 eV (AlN). A way to enhance the flexibility of nitride alloys may be achieved by using AlxGayIn1-x-yN quaternary alloys. The use of AlxGayIn1-x-yN has shown to be an effective way to reduce the defect density in the device since it allows controlling independently the lattice parameter and the band gap of the alloy. In this way, AlxGayIn1-x-yN lattice matched to GaN or AlN may be produced. Based on these features, UV light-emitting diodes and laser diodes consisting of AlxGayIn1-x-yN active layers have been proposed. As observed in the InGaN ternary alloys, phase separation effects and the occurrence of ordered structures may also take place in the AlGaInN quaternaries depending on the growth conditions and alloy compositions. We present in this work a theoretical study by means of ab initio calculations of the energetics, the structural and the thermodynamic properties of AlxGayIn1-x-yN quaternary alloys. The calculations are based on a pseudopotential plane-wave method, within the framework of the density functional theory and the local density approximation, a cluster expansion method in conjunction with either, a generalized quasi-chemical approach and Monte Carlo simulations. Our results are used to clarify the origin and the mechanism of radiative emission observed in recent photoluminescence measurements. Moreover, several physical parameters of AlxGayIn1-x-yN alloys such as lattice constant, bond lengths, bandgap, etc., as functions of the alloy compositions, x and y are predicted.

Y5.71
Comparison of Threading Dislocation Densities in AlGaN and InAlGaN Epilayers by X-Ray Diffraction.
Hun Kang[1], Zhe C. Feng[1], Ferguson Ian[1], S. P. Guo[2], M. Pophristic[2] and B. Peres[2]; [1]Georgia Inst. of Technology, Atlanta, Georgia; [2]EMCORE Corporation, Somerset, New Jersey.

Thick and high composition AlxGa1-xN (x = 0.45 ~ 0.6) layers grown on sapphire by Metalorganic Chemical Vapor Deposition (MOCVD) are commonly used for UV optoelectronics sources. There usually exists a high density of threading dislocations which is the main cause for a low extraction efficiency in LEDs. Therefore it is important to reduce the threading dislocation density in these AlGaN epilayers with developing high efficiency LEDs. In this work, we focus on how to monitor and reduce the dislocation density for high efficiency LEDs. A series of AlGaN thin films were grown on (0001) sapphire by MOCVD. X-Ray Diffraction (XRD) measurements were employed to give a relative measurement of the screw, edge, and mixed components of the threading dislocations below the layers. Two techniques, Williamson-Hall (WH) plot and Reciprocal Space Mapping (RSM), were used to determine and distinguish these dislocations. WH plot can provide information about dislocations characteristics from a linear fit to the Full width at Half Maximum (FWHM) of the triple axis rocking curve (0001) symmetric reflections. The RSM technique is used to obtain the data on a specific reflection. Dislocation densities in these high Al compositions AlGaN epilayers were determined. Through the measurements for AlGaN grown on sapphire with various AlN nucleation layers, the effects of the AlN nucleation layer on the dislocation density in the AlGaN layers were studied and an optimal condition was obtained. It was found that with an increase of Al composition the screw dislocation density increases and edge dislocation density decreases. The incorporation of indium also improved the coherence lengths. In addition, the results obtained from these AlGaN films were compared with that of GaN films grown on (0001) sapphire by MOCVD.

Y5.72
Study on Ultra-fast Carrier Dynamics in InGaN/GaN Quantum Wells with Indium Aggregated Quantum Dot Structures.
Hsiang-Chen Wang[1], Cheng-Yeh Tsai[1], Yung-Chen Cheng[1], En-Chiang Lin[2], C. C. Yang[1,2], Kung-Jen Ma[3], Cheng-Ta Kuo[4] and Jian-Shihn Tsang[4]; [1]Inst. Electro-Optical Eng., National Taiwan University, Taipei, Taiwan; [2]Inst. Electronics Eng., National Taiwan University, Taipei, Taiwan; [3]Dept. Mechanical Eng., Chung Hua University, Hsinchu, Taiwan; [4]Advanced Epitaxy Technology Inc., Hsinchu, Taiwan.

Because of the large lattice mismatch between GaN and InN, their miscibility is quite low, leading to the phenomena of indium aggregation through the process of spinodal decomposition. The indium-rich cluster formation in InGaN compounds results in potential fluctuations and hence the effect of carrier localization. In this paper, we report the experimental results of fsec carrier dynamics based on pump-probe measurements of various InGaN/GaN quantum well samples with various quantum well widths, nominal indium contents, and under various thermal annealing conditions. Quantum dot structures in some of the samples have been confirmed with material analyses. From the room-temperature probe intensity profiles of an annealed sample of 2.5 nm in well width under pumping at different wavelengths, one can see that at a wavelength within the PL spectrum, the transmission intensity drops slowly from its peak. The early-stage faster decay is supposed to be due to carrier relaxation through phonon interaction such that quasi-equilibrium condition is reached. The extended slower decay is attributed to carrier recombination under the quasi- equilibrium condition and its decay time is in the psec-nsec range. During this process, the interaction with acoustic phonons also occurs. At shorter wavelengths for pumping, carrier relaxation to lower energy states becomes faster and more significant. In these situations, the residual carriers become fewer. It is interesting to observe that the oscillations due to acoustic phonon interaction occur only in the temperature range from 100 to 150 K. Also, the LO phonon effect can be observed only when the sample temperature is below around 200 K. Furthermore, we observed see that the level of extended slow decay decreases with increasing temperature. This trend can be attributed to the effective thermal relaxation of carriers into lower-energy states as the pump photon energy is much higher than the photoluminescence emission levels.

Y5.73
Origin and Efficiency of the Photoluminescence of GaN Nanorods.
Xiang-Bai Chen[1], Jesse Huso[1], John L. Morrison[1], Margaret K. Penner[1], Andrew P. Purdy[2] and Leah Bergman[1]; [1]Physics, University of Idaho, Moscow, Idaho; [2]Chemistry Division, Naval Research Laboratory, Washington, District of Columbia.

The photoluminescence (PL) of GaN nanorodes which were

synthesized via an ammonothermal process were studied utilizing UV micro-photoluminescence. For these studies the GaN nanorods were grouped together into ensembles of various sizes ranging from 300 nm up to 60 micrometer. The objective of the studies were to determine the nature of the PL emission as well as its efficiency as a function of ensemble size. The PL spectra at RT of the nanorods exhibit one emission line for which its energy was found to depend strongly on the ensemble size as well as on the laser excitation power: the larger the ensemble size and the higher the laser power, the more redshifted the PL. This phenomenon is discussed in terms of laser heating and light scattering events occurring in an ensemble enclosure. Additionally, the PL intensity as a function of laser power was investigated in order to determine whether the PL of the nanorods is of excitonic origin. It was found that for a small ensemble of nanorods the intensity is almost linear with the laser power; similar behavior was found for GaN film. A linear behavior is indicative of an exitonic rather then a bandgap emission. However, for the large ensembles the PL intensity exhibits a saturation occurring already at relatively low laser power. Our finding will be discussed in terms of the thermal properties of an individual nanorod as well as the collective. Cold temperature studies will be presented as well.

Y5.74

GaN Nanorods: Are They Different from the Base Films?

Hye-Won Seo[1], Quark Y. Chen[1], Xuemei Wang[1], Wei-Kan Chu[1], L. W. Tu[2], C. L. Hsiao[2], T.W. Chi[2], I Lo[2] and K.Y. Shieh[3]; [1]Texas Center for Superconductivity and Dept. of Physics, University of Houston, Houston, Texas; [2]Dept. of Physics, National Sun Yat-Sen University, Kaohsiung, Taiwan; [3]Inst. of Materials Science and Engineering, National Sun Yat-Sen University, Kaohsiung, Taiwan.

Hexagonal in crystal structure, GaN was thought to grow well on a (111) silicon substrate due to similar base plane symmetry. However, because of the high degree of lattice mismatch, GaN nanorods of various geometries were often found to spike out of the base thin film. A natural question to ask then is how these spikes or nanorods are different from the base film. In this work, we conducted a comparative studies on GaN films grown on (111) Si wafers by plasma assisted MBE. After low temperature buffer layer deposition at 500-600 C, high-temperature GaN growth was done at 720 C. The nanorods were observed as bright spikes on a dark background of the base film, which also carried its own striated surface morphology when inspected with different proper contrast and brightness. These silky bright spikes appeared semi-transparent, as the morphology of relevant area of the base film hidden behind the spikes was still observable. We attribute the extra brightness of the spikes in the SE mode to the enhanced secondary electron emission, which arises from the geometric size effect as the scattered electrons have higher probability of escaping from an area of small radius of curvature. In the CL image mode, however, these rods are essentially all dark, while the base material shows as striated bright and grey intermixture. This suggests that the nanorods are indeed more perfect than the base film, as the energy bandgap of high quality GaN falls in the near-UV region, hence the base area, which gives out light more in the visible range, would have to have more defect states to allow for non-radiative relaxation processes before a lower energy radiative process takes place. There are, however, no distinguishable crystallographic differences between the nanorod and base areas as judged from the similar EBSD Kikuchi patterns. The nanorods appeared to be more sensitive to the electron beam irradiation. In this paper, we will also present the electron beam enhanced nanostructure formation and transformation. We thank James Meen for valuable discussion and technical assistances. This work was supported in part by the State of Texas through the Texas Center for Superconductivity at University of Houston, USA and in part by the National Science Council of the Republic of China.

Y5.75

Perturbation-Induced Compositional Instability in III-Nitride Pseudo-Binary Alloy Films. Stephen Roger Lee, Sandia National Laboratories, Albuquerque, New Mexico.

Compositional stability in InGaN alloys is of broad interest for two key reasons. First, compositional instabilities may cause indium-rich domains, which are thought to localize carriers and enhance optical emission in InGaN quantum wells. On the other hand, compositional instabilities in high-indium-content InGaN may actually limit the ability to produce efficient light emitters in the deep-green region of the optical spectrum. Previous studies of compositional stability in III-nitride alloys typically use traditional bulk-spinodal-decomposition models. The resulting chemical spinodal for InGaN predicts alloy instability at 750 degrees-C for InN mole fractions within the range x=0.2 to x=0.8; but, the chemical spinodal overstates the critical temperature because it ignores elastic coherency strains. Extending the analysis to include bulk self-coherency strains yields the well-known coherent spinodal. Since bulk coherence strongly stabilize the alloy, the coherent spinodal predicts that InGaN should in fact be stable at all temperatures and compositions. The opposing predictions of the chemical and coherent spinodals can be reconciled by appealing to recently developed perturbation theories that treat novel elastic effects arising at the free surface of the alloy, but direct application of these models to III-nitrides is limited by the isotropic elasticity theory often used in their formulation. Thus, we are presently modifying these theories to account for anisotropic elastic effects produced by the wurtzite structure of the III-nitrides. We will present preliminary calculations of the critical temperature required for unstable amplification of compositional perturbations in unstrained InGaN, InAlN, and AlGaN films. As in cubic III-V alloys, the perturbation theory predicts that the critical temperature in III-nitride alloys actually lies above the traditional chemical spinodal; moreover, unstrained InGaN is predicted to be unstable near 750 degrees-C for InN mole fractions within the extremely wide range x=0.1 to x=0.9. The U. S. Dept. of Energy, Office of Basic Energy Sciences supports this work. Lockheed-Martin operates Sandia National Laboratories for the DOE (DE-ACO4-94AL85000).

SESSION Y6: Characterization I
Chair: Kazumasa Hiramatsu
Wednesday Morning, December 3, 2003
Room 312 (Hynes)

8:30 AM Y6.1

Polarization-dependent spectroscopy of the near-bandgap emission in free-standing GaN. Plamen Paskov, Tanya Paskova, Per-Olof Holtz and Bo Monemar; IFM, Linkoping University, Linkoping, Sweden.

Recently, with the availability of high-quality free-standing and homoepitaxial GaN layers, the accurate study of free- and bound exciton transitions in GaN become possible. However, so far all of the experiments have been performed with a light wavevector k parallel to the c-axis and then the excitons with a dipole moment perpendicular to c axis are probed. Here, we present results from a study of the edge emission (i.e. with a light wavevector perpendicular to the c-axis) in a free-standing HVPE GaN. Such geometry allows us to examine polarization properties of the optical transitions and to reveal exciton states with different symmetry. For the light polarized perpendicular to the c-axis, the low-temperature PL spectrum reveals the typical emission peaks of the acceptor-bound exciton at 3.4666 eV and the donor-bound exciton at 3.4716 eV as well as a broad emission from the lower polariton branches of the A and B excitons. When the orientation of the detected light is parallel to the c-axis, quite different spectra are obtained. Now, the dominant emission peak occurs at 3.4753 eV. Based on the temperature dependence, the peak is assigned as a donor-bound exciton involving a hole from the B-valence band and its binding energy is found to be 8 meV. In this polarization, the free-exciton emission is dominated by the B exciton-polariton, but a strong enhancement of the emission arising from the lower polariton branch of the C exciton is observed with increasing temperature. The emission lines of the dipole-forbidden spin-triplet state and longitudinal state of the A exciton are also resolved in the spectra. The energies, relative intensities and temperature behaviour of all observed peaks are analysed in terms of the polarization selection rules and the exciton-polariton concept in a wurtzite crystals.

8:45 AM Y6.2

Optical properties of semi-insulating Fe-doped GaN substrates. Olaf Gelhausen[1], M. R. Phillips[1], E. M. Goldys[2], R. P. Vaudo[3] and X. Xu[3]; [1]Microstructural Analysis Unit, University of Technology, Sydney, Sydney, New South Wales, Australia; [2]Division of Information and Communication Sciences, Macquarie University, North Ryde, New South Wales, Australia; [3]ATMI, Inc., 7 Commerce Drive, Danbury, Connecticut.

HVPE-grown GaN substrates with different Fe-doping levels were studied by UV-visible and infrared cathodoluminescence (CL) spectroscopy and monochromatic CL imaging. The CL intensity of the Fe^{3+} emission line at 1.299 eV ($^4T_1 - {}^6A_1$ internal transition) and its multi-phonon sideband structure were found to scale with the Fe concentration and was even detectable at room temperature in samples with high doping levels (1×10^{19} cm^{-3}). Conversely, the shallow donor bound exciton (D^0X) emission intensity at 3.473 eV was reduced in the samples with higher Fe content. In the visible range, several defect emission bands with much weaker CL intensity were observed. The significantly lower CL intensity of the defect emission bands together with the unstrained position of the D^0X emission indicate that the GaN substrates are of high quality. Three defects bands were observed in the sample with the highest Fe-concentration, a blue luminescence (BL) band centered at 2.83 eV, the yellow luminescence (YL) band at around 2.2 eV and a broad green luminescence (GL) band centred at ~2.45 eV. The GL is tentatively assigned to Fe-related defect complexes since it is not observed in nominally undoped HVPE-grown GaN. Monochromatic

detail on the incorporation of C in cubic GaN under extrem Ga rich growth conditions. Cubic GaN is grown by rf-plasma assisted molecular beam epitaxy (MBE) on semiinsulating GaAs (001) substrates. The Ga-rich growth conditions are carefully adjusted by reflection high energy electron diffraction (RHEED). C-doping of the c-GaN is achieved by e-beam evaporation of a graphit rode. Hall-effect measurements and temperature dependent photoluminescence (PL) between 2 K and room temperature are used for characterization. A record hole concentration and hole mobility as high as 6.1x10${18}$cm${-3}$ and 23.5 cm${2}$/Vs, respectively is measured by Hall effect at room temperature. This is the highest hole concentration ever reported for C-doped GaN epilayers. By plotting the room temperature mobility values as a function of hole concentration a compensation ratio of about 0.6 could be estimated. PL-measurements showed a clear enhancement of the near band edge luminescence of cubic GaN:C grown under Ga excess in comparison to that grown under stoichiometrial conditions. This behavior clearly indicate that Ga-rich conditions are advantageous for improved p-type doping.

9:00 AM Y8.3
Above and Below Bandgap Excitation of Er-Defect Complexes and Isolated Er In Er-Implanted GaN.
Alain Braud[1], Jean-Louis Doualan[1], Richard Moncorge[1], Bert Pipeleers[2] and Andre Vantomme[2]; [1]CIRIL-ISMRA, Caen, France; [2]Departement Natuurkunde, Instituut voor Kern-en Stralingsfysica, LEUVEN, Belgium.

Rare-earth doped GaN is being widely studied for its various applications in optoelectronics . Questions still remain about the fundamental understanding of the mechanisms underlying the excitation of rare-earth ions in this host. In order to deepen our understanding of the incorporation of rare-earth ions in GaN and the excitation processes of the 4f-shell, we first investigated the photoluminescence (PL) and photoluminescence excitation (PLE) spectra of the Er3+ 4I13/2  4I15/2 transition in Er-implanted GaN samples at 7K and room temperature. Under below-gap excitation, one type of Er center appears to be predominant while other Er centers are clearly excited via local defects or impurities. The PLE spectra show on one hand that the number of these Er-defect complexes is small compared to the Er predominant center and on the other hand that the defect absorption cross-section is much larger than the typical Er absorption cross-section. Er-defect complexes excited by above or below bandgap light are then compared. Luminescence dynamics show that the 4I13/2 manifold has a shorter lifetime when Er ions are part of Er-defect complexes than when Er ions are isolated from any defect. This result indicates the existence of non-radiative energy transfer in Er-defect complexes from the Er ions towards defects. Classical energy transfer models are successfully used to describe Er dynamics. Comparisons between dynamics of Er-defect complexes excited by above or below bandgap excitation are performed. Luminescence saturation experiments are also carried out. Results are used to derive absorption cross-sections of Er ions or local defects.

9:15 AM Y8.4
Modulation of Arsenic Incorporation in GaN Layers Grown by Molecular Beam Epitaxy.
Sergei V. Novikov[1,2], L. X. Zhao[1], C. T. Foxon[1], B. Ja. Ber[2], A. P. Kovarsky[2], I. Harrison[3], M. W. Fay[4] and P. D. Brown[4]; [1]School of Physics and Astronomy, University of Nottingham, Nottingham, United Kingdom; [2]Ioffe Physical-Technical Institute, St. Petersburg, Russian Federation; [3]School of Electrical and Electronic Engineering, University of Nottingham, Nottingham, United Kingdom; [4]School of Mechanical, Materials, Manufacturing Engineering and Management, University of Nottingham, Nottingham, United Kingdom.

Arsenic doped GaN films grown by plasma-assisted molecular beam epitaxy (PA-MBE) on sapphire substrates show very strong blue emission at room temperature, which is more than one order of magnitude stronger than the band edge emission in undoped GaN films. Our results demonstrate that the growth conditions have a strong influence on the intensity of the blue emission from As-doped GaN grown by PA-MBE. The As incorporation into uniformly As-doped GaN layers was analysed by Secondary Ion Mass Spectroscopy (SIMS) and using GaAs+ secondary ions the As concentration was estimated to between 10(18) and 10(19)cm(-3) depending on the As flux. In this paper PA-MBE growth and properties of GaN layers with modulated As-doping will be discussed. Arsenic periodically-doped GaN layers (GaN/GaN:As/GaN superlattices) with different width of the periods were grown on sapphire substrates. Arsenic incorporation in GaN was analysed using X-ray diffraction, Transmission Electron Microscopy (TEM), SIMS and Photoluminescence (PL). By analysing results from different secondary ions in SIMS studies of As-doped GaN, we show that the quantification procedure for SIMS in this Ga-N-As system depends strongly on the chemistry and microstructure of the sample. SIMS results using different secondary ions clearly confirm the existence of As-modulation in the GaN/GaN:As structures. The modulation of As doping strongly influences the optical properties of GaN/GaN:As superlattices. PL spectra of both the blue emission and the band edge emission are modified with increasing of the period of GaN/GaN:As superlattice and these changes will be discussed.

9:30 AM Y8.5
Optical Properties of Mn-doped GaN.
Olaf Gelhausen[1], E. Malguth[1,3], M. R. Phillips[1], E. M. Goldys[2], M. Strassburg[3], A. Hoffmann[3], T. Graf[4] and M. Stutzmann[4]; [1]Microstructural Analysis Unit, University of Technology, Sydney, Sydney, New South Wales, Australia; [2]Division of Information and Communication Sciences, Macquarie University, North Ryde, New South Wales, Australia; [3]Institute for Solid-State-Physics, Technical University Berlin, Berlin, Germany; [4]Walter Schottky Institute, Technical University Munich, Munich, Germany.

The optical properties of molecular beam epitaxy-grown GaN with different Mn-doping levels (5-23 x 10^{19} cm^{-3}) were studied by UV-visible and infrared cathodoluminescence (CL) spectroscopy and optical transmission measurements. Transmission measurements at 2 K revealed an absorption peak at an energy of 1.414 $\pm$ 0.002 eV, which was attributed to a photoionization process by internal absorption from the Mn^{3+} ground state to an excited state. This assignment is supported by the absence of this transmission peak in GaN:Mn samples codoped with Si, where an electron transfer process from the Si donor to the Mn acceptor takes place. The intensity of this Mn-related transmission peak was found to scale with the Mn^{3+} concentration. The CL measurements showed that Mn-doping concentrations around 10^{20} cm^{-3} reduced the donor bound exciton emission intensity by more than one order of magnitude and also completely quenched both the shallow DAP band at 3.27 eV and the yellow luminescence centered at 2.2 eV. Additionally, the Mn-doped GaN exhibited a reduced intrinsic conductivity since electron beam induced charging was observed. In the infrared spectral range of 0.8 - 1.4 eV three broad, Mn-doping related CL emission bands centered at 1.03 eV, 1.09 eV and ~1.3 eV were observed, which were found to be highly beam sensitive. The GaN:Mn with the highest doping levels displayed the strongest IR emission intensity. These infrared CL bands were also observed in the GaN:Mn codoped with Si, but not in the nominally undoped sample, suggesting that their origin is related to deep level structural defects with strong phonon coupling rather than to the charge transfer processes involving the Mn^{3+} acceptor itself.

9:45 AM Y8.6
Magnetic Properties of Mn-doped GaN, InGaN, and AlGaN.
Meredith L. Reed[1], E. Acar Berkman[2], Mason J. Reed[2], F. Erdem Arkun[2], Salah M. Bedair[3], John M. Zavada[4] and Nadia A. El-Masry[2]; [1]Electrical and Computer Engineering, National Research Council and North Carolina State Univeristy, Raleigh, North Carolina; [2]Department of Materials Science and Engineering, North Carolina State Univeristy, Raleigh, North Carolina; [3]Department of Electrical and Computer Engineering, North Carolina State Univeristy, Raleigh, North Carolina; [4]Army Research Office, Research Triangle Park, North Carolina.

We report on the growth and magnetic properties of single crystal Mn-doped GaN, InGaN, and AlGaN films. The III-Nitride films were grown by metal-organic chemical vapor deposition, while the Mn doping was performed by solid-state diffusion of a surface Mn layer deposited by pulsed laser ablation. Mn-doped $In_xGa_{1-x}N$ films were grown with $x < 0.15$, where the easy axis of magnetization depends on the stress state of the $In_xGa_{1-x}N$ film. The easy axis rotates from in-plane to out of plane by changing the film thickness thus going from strained to fully relaxed films. Mn-doped $Al_xGa_{1-x}N$ films were grown with $x < 0.40$ showing ferromagnetic behavior above room temperature. Temperature dependent superconducting quantum interference device measurements confirmed the absence of superparamagnetism within the films. By optimizing the growth and annealing conditions of Mn-doped III-Nitrides, we have achieved Curie temperatures in the range of 228 to 500K. These Mn-doped III-Nitride films have ferromagnetic behavior with hysteresis curves showing a coercivity of 100-500 Oe. Transmission electron microscopy confirmed the absence of any secondary phases within the films used in this study. Hall Effect measurements showed that magnetic properties exist in both insulating and n-type films.

10:30 AM *Y8.7
Configurations and Properties of Oxygen Impurities in Wurtzite GaN.
Alan Francis Wright, Sandia National Laboratories, Albuquerque, New Mexico.

Atomic configurations corresponding to local-energy minima for an isolated O atom in wurtzite GaN are identified using density-functional theory and the generalized-gradient approximation for exchange and correlation. Formation energies computed for these

configurations as a function of the charge state are used to estimate defect energy levels in the gap and to predict the dominant O configuration as a function of Fermi level. Substitutional, interstitial, and DX configurations are examined and the interaction of H with these configurations is explored. Energy barriers are also reported for O migration through the lattice. This work was partially supported by the Office of Basic Energy Sciences, U.S. Dept. of Energy. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Dept. of Energy under Contract DE-AC04-94AL85000.

11:00 AM Y8.8
Efficient p-type doping of GaN films by MBE.
A Bhattacharyya[1], Wei Li[1], C Thomidis[1], T D Moustakas[1] and David J Smith[2]; [1]Electrical Engineering, Boston University, Boston, Massachusetts; [2]Center for Solid State Science and Department of Physics and Astronomy, Arizona State University, Tempe, Arizona.

The efficient P-type doping of GaN and its alloys with InN and AlN is still one of the most challenging problems during the fabrication of both electronic and optical devices based on this class of materials. This is partly due to the problems associated with the deep nature of Mg acceptors as well as to compensation during doping of wide band-gap semiconductors, which cause a reduction in hole mobility. Reports in the literature indicate that the room-temperature resistivity of Mg doped P-type films grown either by MOCVD or MBE has been typically more than 1 ohm-cm. In this paper we report enhanced efficiency of Mg doping during growth of GaN films by plasma assisted molecular beam epitaxy. These films were grown in Varian GenII system with standard effusion cells and an Applied-Epi RF plasma source for nitrogen activation. The investigated films were grown with Ga BEP up to 1.2E-6 Torr, RF plasma power of 450 Watts, and a substrate temperature of 770C. The Mg flux was varied from 2.0E-8 to 1.2E-7 Torr. The films were studied by SIMS analysis, room and low temperature Hall effect, Fourier Transform spectroscopy and photoluminescence measurement. Our data show strong correlation between Mg-incorporation and ratio of III-V fluxes. We have obtained films with room-temperature hole concentrations ranging from 1.0E+17 to 2.0E+18 /cm3, with corresponding mobilities ranged from 30 to 6 cm2/Vs. The best resistivity obtained was around 0.2 ohm-cm, which is a significant improvement on the typical values reported in the literature. Furthermore FTS transmission measurements indicate that the films doped p-type 1.0E+18/cm3 exhibit an abrupt band-edge with no evidence of band-tailing. This is of vital importance when these films are used as part of vertically emitting LEDs, LDs and UV photodetector structures. We have also conducted detailed PL measurements on these samples. It is well known that highly doped as-deposited films by MOCVD or MBE generally exhibit weak luminescence at room temperature. Upon annealing at high temperature for dopant activation, the MOCVD films show a strong and broad blue luminescence. In this paper we report highly doped GaN films which exhibit a narrow band-edge luminescence as well as D-A transitions attributed to Mg doping. The peak positions and relative intensities have been correlated to the Mg doping levels in these films.

11:15 AM Y8.9
A Critical Look at Hole Transport in Mg-doped GaN*.
Carleton H. Seager[1], Dan Koleske[2] and Andy Allerman[3]; [1]01111, Sandia National Laboratories, Albuquerque, New Mexico; [2]01126, Sandia National Laboratories, Albuquerque, New Mexico; [3]01126, Sandia National Laboratories, Albuquerque, New Mexico.

High p-layer conductivity is critical for achieving high power operation of GaN and AlGaN based LEDs. Most past work has focused on maximizing the incorporation of Mg dopants in this material, and problems with achieving purely substitutional site occupation have been identified. However, an equally, if not more important issue is the low hole mobility usually seen in Mg-doped GaN samples. Hall mobilities greater than 15 $cm^2/V.sec$ at 300K are almost never reported, despite the fact that mobilities ~10x larger have been demonstrated[1] for p-type hexagonal GaN grown by ion-assisted MBE. Because of the relatively low carrier densities in Mg-doped GaN, ionized dopant scattering is not expected to reduce mobilities to the values actually observed, so these extremely low values remain largely unexplained. We have grown hetero-epitaxial GaN layers doped with Mg and Si and with Mg alone and measured hole transport properties as a function of temperature. We have paid particular attention to the influence of electron transport in the nucleation layers below the p-type GaN in reducing the apparent mobility seen in our Hall measurements. Modeling of these data suggest that the reduction in mobility seen by deliberately introducing ~5-10 x 10^{18} compensating donors, while noticeable, is not particularly severe, suggesting that substantinl unintended compensation may already be present. We will also report transport measurements on Mg-doped GaN which has been activated (hydrogen de-passivated) by several non-standard methods and discuss the implications for substantially improving the mobility of holes in this material. L. M. Rubin et al, Appl. Phys. Lett. **64**, 64 (1994). *This work was supported by the Basic Energy Sciences Office of the Department of Energy. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-ACO4-94AL85000.

11:30 AM Y8.10
Hydrogen Release and Isotope Exchange by p-GaN in Vacuum, N2, O2, and H2: Experiment and Theory.
Samuel M Myers, Bastiaan L Vaandrager, Carleton H Seager and William R Wampler; Sandia National Laboratories, Albuquerque, New Mexico.

The release and isotope exchange of H by p-type GaN(Mg) during exposure to vacuum, N2, O2, and H2 has been measured and quantitatively described by a unified theoretical model. The resultant understanding bears on the optimization of acceptor-activation anneals in device processing. Using deuterium with nuclear-reaction analysis permitted release isotherms to be followed over two decades in bulk concentration, facilitating the determination of kinetics. Surface accumulation of oxygen was quantified by employing O-18 with nuclear-reaction analysis. IR spectroscopy of the Mg-H complex probed the concentrations of both protium and deuterium during isotope exchange. All results are quantitatively consistent with a model whereby H in bulk solution equilibrates rapidly with a small population in surface sites, so that adsorption and desorption limit the movement of H to and from solution. In high vacuum and UHV, the desorption is predominantly by H-H recombination and is second-order in H surface coverage, as previously reported by us. Lengthy vacuum isotherms additionally reveal an emerging first-order H-desorption process, provisionally attributed to the release of N-H species. N2 at atmospheric pressure increases the first-order contribution by several times, possibly through an enhanced density of reactive surface N. O2 has a much larger effect, accelerating H release by more than a decade at pressures in the torr range. O2 isotherms indicate first-order H desorption initially, consistent with the release of O-H species. The release then slows abruptly, correlating with the buildup of O as expected for oxide-blocking. Isotope exchange between solution and external H2 gas is orders of magnitude faster than release into vacuum, confirming H-H recombination as the dominant rate-determining step in release. Supported by the Office of Basic Energy Sciences, US DOE. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US DOE under Contract DE-AC04-94AL85000.

11:45 AM Y8.11
Mg Doped GaN Using A Valved, Thermally Energetic Source: Enhanced Incorporation, Control and Quantitative Optimization. Shawn Burnham[1], G. Namkoong[1], W. A. Doolittle[1] and A. S. Brown[2]; [1]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [2]Duke University, Durham, North Carolina.

P-type GaN has traditionally been grown by molecular beam epitaxy (MBE) with Mg as the dopant, using an effusion cell with the flux a function of the cell temperature. However, due to the high vapor pressure of Mg, it is difficult to control the flux using cell temperature alone. Given the small sticking coefficient and surface accumulation issues related to Mg doped GaN, it may be beneficial to have a more reactive species of Mg impinging on the sample surface. Unfortunately, with conventional effusion cells, the flux and flux energy are coupled together through the cell temperature. It would be ideal to control the flux separately from the flux energy, as well as attenuate the flux independently of the cell temperature with a valve control. In this study, a thermally energetic Mg source with a valved flux control is used to vary the Mg concentration in GaN. Mg flux is varied, retaining a constant thermal energy, from 1e-10 Torr beam equivalency pressure (BEP) to well above the saturation limit[1] (3e-9 Torr BEP) in steps separated by undoped GaN layers. To observe effects of the thermal energy of the Mg flux on Mg incorporation, two Mg temperatures were investigated: one well above the melting point of Mg (900°C) and one slightly below the melting point of Mg (625°C). Results were analyzed using secondary ion mass spectrometry (SIMS). For a constant BEP, the incorporated Mg increased by greater than ten times when the Mg thermal source temperature was raised from 625°C to 900°C. During SIMS analysis, the energy spectra of sputtered atoms shifts at a flux slightly below the critical flux for saturation, possibly providing a quantitative means of optimizing p-type conduction. This effect may be related to a change in sample charge incurred from a transition from insulating to conducting layers. [1]G. Namkoong, W. A. Doolittle, and A. S. Brown, Applied Physics Letters 77, 4386 (2000).

SESSION Y9: Characterization II
Chair: Nadia El-Masry
Thursday Afternoon, December 4, 2003
Room 312 (Hynes)

1:30 PM Y9.1
High optical efficiency GaN layers on O and Zn face ZnO.
Xing Gu[1], Faxian Xiu[1], Michael Reschikov[1], Lei He[1], Feng Yun[1], Daniel Johnstone[1], Jeff Nause[2] and Hadis Morkoc[1]; [1]Electrical Engineering, Virginia Commonwealth University, Richmond, Virginia; [2]Cermet Inc., Atalanta, Georgia.

ZnO is a highly efficient photon emitter, has optical and piezoelectric properties that are attractive for a variety of applications. Due to its stacking order and close lattice to GaN, it is also considered as a substrate material for GaN epitaxy. In the past the poor preparation of ZnO surface has been a major handicap to GaN epitaxy. However, a treatment we developed renders both O and Zn faces of ZnO smooth with atomic scale terraces. Epitaxy of GaN on O-face and Zn-face ZnO by reactive molecular beam epitaxy was performed. We used low-temperature RF growth of GaN buffer layer on ZnO surface to protect it from both ammonia and Ga. No Ga2ZnO4, an oxide with the spinel structure, formed due to reaction of ZnO with Ga, was found, in contrast to earlier reports. The low-temperature photoluminescence (PL) indicates that both faces of ZnO lead to GaN with high radiative efficiency. In the previous research it has been reported that O-face ZnO is slightly better for GaN epitaxy. Our new finding demonstrates that high-quality GaN epilayers can be grown on Zn face of ZnO as well indicating the efficacy of the surface treatment. In particular, contribution of the donor-accepter-pair PL band in GaN on Zn-face ZnO is lower that that on O-face ZnO, although both of them are in pretty low level compared with the exciton peak. This can be attributed to a reduced O-background doping into GaN from Zn-face ZnO compared with O-face ZnO.

1:45 PM Y9.2
Structural and optical characterization of (InGa)N layers grown by MOMBE.
Pierre Ruterana[1], Protima Singh[1], Jochen Aderhold[2], Jurgen Graul[2] and Valery Yu. Davydov[3]; [1]LERMAT, ENSICAEN, Caen, France; [2]University of Hannover, LFL, Hannover, Germany; [3]IOFFE, St Petersburg, Russian Federation.

Nitride semiconductors (AlN, GaN, InN and their alloys) have great potential for use in optical devices and high-power, high-frequency electronic devices. Among these nitrides, InN has the smallest effective mass and the highest electron drift velocity. Which sets it as a very promising material for the channel layers in high-speed and high-frequency electronic devices. However, difficulties in growing high quality InN films have hindered the understanding of the properties of InN and their applications. During the past few years, the development of growth techniques, especially in molecular beam epitaxy (MBE), have significantly improved the quality of InN films attaining Hall mobility beyond 2100 cm2/Vs and carrier concentration close to 3*1017/cm3 at room temperature. In these high quality InN films, a narrow bandgap (<0.7 eV) has been reported. However structural properties of InN films such as defects, interface, crystallinity, polarity etc. have been studied rather poorly. In this work, we investigate the microstructure, defects and growth modes of (In, Ga)N films grown by MBE using transmission electron microscopy (TEM). Thick ternary films were successively grown for an indium fraction varied from 6% to 100%, we analyze the evolution of the layer structure versus the indium composition. We correlate the results of surface roughness analysis by AFM to the TEM measurements of the surface morphology. The overall crystal state is investigated also by XRD and correlated to TEM imaging and diffraction for a complete determination of the nature of defects inside the layers and their distribution versus the In composition. PL measurement allow us to follow the evolution of the band gap energy.

2:00 PM Y9.3
The Structure of Dislocations in GaN Grown by MBE as a Function of the Gallium to Nitrogen Ratio.
Marcus Q. Baines[1], David Cherns[1] and C Thomas Foxon[2]; [1]HH Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom; [2]Dept Physics and Astronomy, University of Nottingham, Nottingham, United Kingdom.

Determining the core structure and surroundings of dislocations is of great interest in understanding their electrical properties. In previous work [Baines et al, Mat. Res. Soc. Symp. Proc. Vol. 743 L2.5, (2003)] we showed that GaN films grown under Ga-rich conditions contained open-core dislocations, whereas dislocations in Ga-lean samples were closed-core. In this work we investigate samples grown with a range of Ga pressures by molecular beam epitaxy (MBE) on GaN templates on sapphire substrates. The surface morphology was studied by atomic force microscopy (AFM). This showed that in samples grown under Ga-rich conditions surfaces were generally smooth but with a few well-spaced and pronounced pits. In contrast, samples grown under Ga-poor conditions were much rougher on a fine scale. Transmission electron microscopy (TEM) images taken on plan view samples were in good agreement with the AFM results. These studies also showed that the pits observed in Ga-rich samples extended into the foil, and were generally but not always associated with threading dislocations. More detailed studies showed that some of these open core dislocations had edge or a-components of the Burgers vector, in contrast with previous work showing that hollow core dislocations are exclusively of screw type [Cherns et al, J Cryst Growth 178 (1-2): 201-206 (1997)]. The pits were often hexagonal at the intersection with the surface and were sometimes decorated with an amorphous deposit believed to be Ga-rich. Conversely, in samples grown under Ga-poor conditions there was no evidence that dislocations were correlated with extended surface pits. The paper will describe how the structure of the dislocations changes with the Ga/N ratio and the nature of the amorphous deposits.

2:15 PM Y9.4
Atomic Scale Characterization of Impurity Segregation and Electronic Structure Changes at Dislocations in GaN.
Ilke Arslan[1], Serdar Ogut[2] and Nigel D Browning[3,4]; [1]Physics, University of California-Davis, Davis, California; [2]Physics, University of Illinois, Chicago, Illinois; [3]Chemical Eng. & Matls Science, University of California-Davis, Davis, California; [4]National Center for Electron Microscopy, Lawrence Berkeley National Lab, Berkeley, California.

Despite an intense research effort for more than a decade, the fundamental role of dislocation cores in GaN is still the subject of strong debate. Although GaN-based light emitting diodes (LEDs) and lasers are currently being fabricated, device failure is the principle cause of continued research into the relationship between structure and properties of threading dislocations. Furthermore, impurity segregation to dislocation cores is an important and understudied subject area, particularly for prevalent impurities such as oxygen. To study these effects, a detailed atomic scale characterization of the structural and electronic properties has been performed experimentally using the simultaneous atomic resolution Z-contrast imaging and electron energy loss spectroscopy (EELS) techniques in a scanning transmission electron microscope (STEM), and theoretically using density functional theory (DFT) calculations. Previous simulations indicated that intrinsically there are no states formed in the band gap, and hence stoichiometric cores are not responsible for electrical activity. With these simulations as a basis, atomic resolution experiments were performed on three variants of screw dislocations: the open core, the partially filled core, and the full core. In the open core, oxygen was found to be present at the edges of the core, having the strongest concentration at the surface layers, but continuing for approximately 20 monolayers into the sample. The partially filled core had a weaker, but measurable oxygen signal, and the full core was not found to contain oxygen within the detection limits. These oxygen impurities create states in the band gap, and hence appear to be the origin of the unwanted electrical activity at the cores. The results suggest that this electrical behavior primarily arises from the open and partially filled cores, which are much less prevalent than the filled cores, and may explain the initial insensitivity of GaN devices to the high density of threading dislocations.

2:30 PM Y9.5
Microstructure of Thick InGaN Epitaxial Layers.
Lijian Geng[1], Sridhar Srinivasan[1], Rong Liu[1], Bin Jiang[1], Hiromasa Omiya[1], Fernando A. Ponce[1], Shinji Tanaka[2] and Yoshinori Nakagawa[2]; [1]Physics and Astronomy, Arizona State University, Tempe, Arizona; [2]Nichia Corporation, Anan, Tokushima, Japan.

InGaN quantum wells used in the active region of light emitting devices are usually grown under conditions far from equilibrium. Their microscopic properties are not well understood due to the fact that the layers are severely strained and exhibit strong piezoelectric fields, and to the lack of information about bulk properties of these alloys. Knowledge of the microstructure of InGaN thick layers is limited at the present time due to the difficulty in growing high-quality thick films. In this study we have studied the microstructure of 100 nm thick InGaN films using TEM. The layers were grown on GaN on sapphire using MOCVD with the indium compositions ranging from 0.03 to over 0.22 as determined by Rutherford backscattering spectroscopy. We observe significant changes in the microstructure as the indium composition is varied. Samples with indium composition below 0.09 are highly homogeneous. Samples grown in the range 0.09 to 0.17 exhibit a mostly homogeneous matrix with isolated indium-rich regions in the vicinity of pits at the termination of threading dislocations. For compositions above 0.17, there is a breakdown in the crystalline structure and the layer is polycrystalline in nature. Our observations of microstructure closely follow solid phase miscibility calculations for InGaN published in the literature. This study gives a fundamental understanding of the nature of these materials and could be useful in solving key issues

associated with the growth of high-quality InGaN.

2:45 PM Y9.6
Dislocation Propagation and Strain Relaxation in GaN Films on Porous SiC. Ashutosh Sagar[1], Randall M Feenstra[1], C. K. Inoki[2], T. S. Kuan[2], F. Yun[3] and H. Morkoc[3]; [1]Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania; [2]Physics, University at Albany, SUNY, Albany, New York; [3]Electrical Engineering, Virginia Commonwealth University, Richmond, Virginia.

We have grown GaN on porous SiC substrates and studied the effect of substrate porosity on the overgrown film quality in terms of defect structure and film strain. The growth was performed by both plasma-assisted molecular beam epitaxy and reactive molecular beam epitaxy. The GaN films were characterized by x-ray diffraction, transmission electron microscopy (TEM) and wafer curvature measurements by surface profilometry. TEM images show that the GaN film grown on porous substrates contains open tubes and a relatively low dislocation density in regions between tubes. The open tubes originate from the pores of the SiC. We discuss various growth mechanisms that can lead to these defect features in the GaN film. We do not find any overall improvement in the x-ray rocking curve FWHM of the GaN films grown on porous substrates compared to those on nonporous substrates. However, it was found that the GaN films grown on porous SiC were significantly more strain relaxed compared to those grown on nonporous substrate. We attribute this strain relaxation not to elastic relaxation of the porous layers, as suggested by some prior authors, but rather to enhanced formation of strain-relieving dislocations near pores due to concentration of stress near the pores. The additional dislocations needed to relieve strain in the films grown on the porous layers are observed in the form of half-loop dislocations originating at the walls of open tubes in the GaN films. The half-loop dislocations glide in from the tubes. The Burgers vectors of the half-loops indicate that they are strain relieving. As a model for the observed strain reduction, we propose that the half-loops nucleate (and glide) as long as the stress energy in the film is sufficiently high, and as soon as the stress is relieved by a sufficient number of these dislocations then no more will be formed and the film strain remains constant. To verify the role of the tubes in the GaN films as "stress concentrators" we have performed finite element analysis of a strained film containing such tubes. We do indeed find an increase in the tangential component of the stress at the tube walls, increasing e.g. by about a factor of two for a 5% porous film. For the same film, the average in-plane component of the strain changes only slightly, demonstrating that elastic relaxation (due to the presence of the tubes) does not contribute significantly to overall strain reduction in the film.

3:30 PM *Y9.7
Atomic Structure of Defects in GaN:Mg; Influence of Annealing. Zuzanna Liliental-Weber[1], Tomasz Tomaszewicz[1], Dmitri Zakharov[1], Jacek Jasinski[1], Michael O'Keefe[1] and Kimmo Saarinen[2]; [1]Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California; [2]Helsinki University of Technology, Espoo, Finland.

A direct reconstruction of the phase and amplitude of the scattered electron wave from a focal series of high-resolution images was applied to determine the nature of defects formed in GaN:Mg bulk crystals grown from dilute solution of atomic nitrogen in the liquid gallium at high pressure and also in crystals grown by MOCVD method. Crystals grown with Ga-polarity were studied. The majority of defects are three dimensional Mg-rich pyramids with their base on the (0001) plane and six walls which, on average, can be described as {11-23} planes. Detailed high resolution study show formation of facets or the formation of dome shaped-figures on the side walls. Some of these defects appear in cross-section as rectangular defects. These defects are terminated by c-planes. Such defects can be parts of pyramids in thin TEM foils or can be formed from large clusters of Mg accumulated on the c-plane. These two shapes of defects observed in cross-section foils cannot be distinguished in plan-view observation. The density of pyramidal defects depends on Mg concentration but their distribution within the crystal is not always uniform. Formation of new pyramidal defects can be observed upon annealing. Correlation of these results with photoluminescence studies performed on the same crystals will be presented. The mechanism of formation of these defects is rather complex. Very often the thickness within the defects is smaller than surrounding matrix, and some of them have empty holes within the defects. Our recent studies using focal series of high-resolution images, which allows one to distinguish between Ga and N atoms, showed that some of these defects are inversion domains and other are not. It will be shown that inversion areas are close to the pyramid walls but the center of the defects can be empty or can show slightly modified composition. Since growth rate with N polarity is slower then growth with Ga-polarity (characteristic for the matrix), it is not surprising that some empty areas can be formed within these defects. Formation of empty holes in GaN:Mg was also confirmed by positron annihilation study. The models of the inversion initiated from the side walls and reversing the polarity on the base of the defect, which allows further growth with the matrix polarity, will be presented.

4:00 PM Y9.8
Influence of Growth Parameters on the Deep Level Spectrum in MBE-Grown n-GaN. Aaron Arehart[1], C. Poblenz[2], B. Heying[2], J. S. Speck[2], U. K. Mishra[2], S. P. DenBaars[2] and S. A. Ringel[1]; [1]Department of Electrical Engineering, The Ohio State University, Columbus, Ohio; [2]Materials and Electrical and Computer Engineering Departments, University of California, Santa Barbara, California.

The impact of growth temperature and Ga/N flux ratio on deep levels in GaN grown by molecular beam epitaxy (MBE) is systematically investigated using both deep level optical spectroscopy (DLOS) and deep level transient spectroscopy (DLTS) in a study designed to map out the presence and concentration of defects over a defined region of the MBE GaN growth phase diagram. A series of Si-doped GaN films were grown to cover a substrate temperature range and a Ga/N flux ratio range that spans from the N stable to the Ga droplet regimes along both variables. Identical growth templates were used to eliminate variations in dislocations between samples so that point defect variations could be tracked. For all samples, traps are detected at E_C-E_t=0.25, 0.60, 0.90, 1.35, 2.40, 3.04, and 3.28 eV. The near valence bands states at E_C-3.04 and E_C-3.28 eV are found to be strongly dependent on Ga/N flux with decreased concentrations as a function of increasing Ga flux toward the Ga droplet regime, but with little effect from growth temperature. In contrast, the concentration of the E_C-E_t=0.25, 0.90 eV levels increases with increasing Ga flux toward the Ga droplet regime but with a similar lack of dependence on growth temperature. The E_C-E_t=0.60 and 1.35 eV levels show altogether different behavior with higher concentrations at increased growth temperature, but with no appreciable dependence on the Ga/N flux ratio. The variation in concentration of the E_C-2.40 eV level that has been attributed to V_{Ga} is difficult to quantify, but no strong correlation with growth parameters is observed over the range studied. The dependencies for the detected states with respect to growth temperature and Ga/N flux ratio suggest different physical point defect sources, which will be discussed in detail in the context of growth conditions and the growth phase diagram.

4:15 PM Y9.9
Morphology, Microstructure, and Mechanisms of Strain Relaxation of AlN Interlayers in AlGaN/GaN on Sapphire. Karen E. Waldrip[1], S. R. Lee[1], J. A. Floro[1], D. M. Follstaedt[1], J. Han[1,5], A. J. Fischer[1], D. D. Koleske[1], A. A. Allerman[1], D. J. Smith[2], U. Chowdhury[3], R. D. Dupuis[3], B. P. Gila[4] and C. R. Abernathy[4]; [1]Physical and Chemical Sciences Center, Sandia National Laboratories, Albuquerque, New Mexico; [2]Department of Physics and Astronomy, and Center for Solid State Science, Arizona State University, Tempe, Arizona; [3]Department of Electrical and Computer Engineering, University of Texas Austin, Austin, Texas; [4]Department of Materials Science and Engineering, University of Florida, Gainesville, Florida; [5]Yale University, New Haven, Connecticut.

Cracking of AlGaN on GaN due to tensile strain and its consequences for device performance is a well-documented problem. Thin interlayers of AlN inserted between the AlGaN and GaN layers have been shown to suppress cracking in AlGaN. It has been suggested in the literature that the AlN relaxes during growth, thereby producing a template with a new (smaller) lattice constant for further growth. Cross-section transmission electron microscopy (TEM) measurements reveal about a 10X increase in threading dislocations with burgers vector $\mathbf{b} = \mathbf{a}$ in the crack-free AlGaN overlayers. In order to investigate the origin of these dislocations, we present a detailed characterization of the AlN/GaN interface for several thicknesses of AlN deposited at high temperature (1050C). Data collected from atomic force microscopy, high-resolution TEM, high-resolution x-ray diffraction, and in situ stress measurements are combined to elucidate the mechanisms of stress relaxation of AlN on GaN grown on sapphire by MOCVD. It is found that AlN growth proceeds two dimensionally for the first few monolayers, after which it undergoes a morphological transition producing islands approximately 50-100 nm wide. Geometrical arguments regarding island size and shape indicate that, depending upon thickness, 90% or more of the strain relaxation of the AlN interlayers can be accounted for by morphology. Cross-section TEM lattice images showed that the AlN islands are coherent, indicating that no misfit dislocations are present at the AlN/GaN interface immediately prior to AlGaN overlayer growth. Morphological relaxation of the coherent AlN creates inhomogeneous strain fields that may provide additional pathways for the nucleation of strain relieving dislocations, as well as non-zero Peach-Koehler forces that enable dislocation glide along first order slip systems in the compressively strained AlGaN overlayers. The results from this study will be discussed in terms of optimization of interlayer design for optical devices. This work was partially supported by the DOE Office

of Basic Energy Sciences. Sandia is a multiprogram laboratory of the United States Department of Energy operated by Sandia Corporation, a Lockheed Martin Company, under contract DE-AC04-94AL85000.

4:30 PM Y0.10
Strain distribution in GaN/Si(111) epilayers with inserted SiN. Axel Hoffmann[1], Ute Haboeck[1], Christian Thomsen[1], Till Riemann[2], Frank Bertram[2], Juergen Christen[2], Armin Dadgar[2] and Alois Krost[2]; [1]Inst. f. Fstkoerperphysik, TU Berlin, Berlin, Germany; [2]Institut fuer Experimentelle Physik, Otto-von-Guericke Universitaet, Magdeburg, Magdeburg, Germany.

Control of strain distribution and eliminating of crack formation is essential for the growth of high quality GaN/Si epilayers. The lattice mismatch between epilayer and substrate and in particular the different thermal expansion coefficients are origin of tremendous tensile stress. The insertion of low-temperature AlN [1] combined with ultra-thin SiN interlayers [2] is a promising design method to overcome these problems [3]. To investigate their impact on the structural and optical properties series of GaN/Si(111) samples with different interlayer design grown by metalorganic chemical vapor phase epitaxy (MOCVD) were investigated using micro-Raman spectroscopy and cathodoluminescence microscopy (CL). Samples with identical growth sequences but consecutively increasing deposition time of the final GaN layer enable a systematic analysis of the strain evolution step by step. The Raman spectra in the vicinity of the E2(high) mode are a common powerful tool for probing the strain distribution. The final growth procedure starts with isolated GaN islands on the SiN, which are almost stress free. With increasing coalescence tensile stress evolves and increases with GaN layer thickness. The micro-Raman results are in perfect agreement with the CL. Despite the observed tensile stress of the thicker GaN layers we found no indication for cracks. Moreover no impurity incorporation, which would result in high local carrier concentration are found in the Raman spectra. Changing the sample design by inserting a GaN/LT-AlN prior to the deposition of the SiN interlayer results in two E2(high) peaks in the spectra: one originating from the compressively strained template and the other from tensile strained final the GaN layer. The dependence of the GaN domain geometry on the SiN interlayer thickness is quantitatively evaluated. [1] A. Dadgar, et al., Jpn. J. Appl. Phys. Part 2 39, L1183 (2000). [2] S. Haffouz, et al., Appl. Phys. Lett. 73, 1278 (1998). [3] A. Dadgar, et al., Appl. Phys. Lett. 82, 28 (2003).

4:45 PM Y0.11
Temperature-dependent Surface Potential Microscopy- an Approach to Determine the Thermal Activation Energy of Dislocation-related Levels in GaN Layers. Andre Krtschil, Armin Dadgar and Alois Krost; Institute of Experimental Physics, Otto-von-Guericke-University of Magdeburg, Magdeburg, Germany.

Threading dislocations in epitaxial GaN layers, their properties, and their impact to device parameters are subject of tremendous research activities. However, there is still a lot of confusion on the electrical properties of dislocations and, moreover, on the position of related levels within the bandgap. In this paper, we present an approach to determine the thermal activation energy of such dislocation-related levels. This technique bases on common scanning surface potential microscopy (SSPM) analysis and is performed for different sample temperatures between room temperature and 330 K. In principle, a selected region of the sample is scanned at different fixed temperatures and the potential peak in SSPM due to the dislocation-related charge is studied. Assuming a simple Arrhenius-like dependence of the peak height on the reciprocal temperature, the thermal activation energy of the related levels corresponds to the slope of the fit curve. This method was applied to GaN layers which are grown by metal organic vapor phase epitaxy on c-axis oriented sapphire substrates and which are differently doped, i.e. undoped, Si-doped, or Mg-doped. For screw-like dislocations in Mg-doped layers we determined a thermal activation between 60 and 100 meV. Despite of a quite linear fit curve, these activation energies are too small to correlate either to the dislocation-related levels itself, which should be located deeper within the gap, or to the magnesium acceptors from the surrounding regions. However, extensive studies on native point defects, especially on the nitrogen vacancy, revealed a similar thermal activation energy. This suggests that nitrogen vacancies are accumulated around the core charge and dominate the temperature behavior. The results for undoped and Si-doped layers as well as the differences compared to the p-type films will be discussed in detail, too.

SESSION Y10: Poster Session
Thursday Evening, December 4, 2003
8:00 PM
Exhibition Hall D (Hynes)

Y10.1
Silicon Doping of High Mole Fraction $Al_xGa_{1-x}N$ (x>0.45) for Ultraviolet Optoelectronic Devices. Mark Johnson[1], Yogananad Saripalli[1], X-Q Liu[1], A Cai[2] and J.F. Muth[2]; [1]Material Science and Engineering, NC State University, Raleigh, North Carolina; [2]Electrical and Computer Engineering, NC State University, Raleigh, North Carolina

Deep UV-light emitters and photodetectors based on $Al_xGa_{1-x}N$ wide-bandgap semiconductors have attracted much attention for applications such as bio-optical detection and ultraviolet imaging in the 250nm - 280nm spectral region. Many devices proposed for these application require both n-type and p-type conductivity of $Al_xGa_{1-x}N$ with compositions exceeding x=0.45. Approaches to achieving these doping levels have included both maximization of the Metal-Organic Chemical Vapor Deposition (MOCVD) process-space and development of unique functional heterostructures, which are used in optoelectronic devices. For n-type doping, silicon is the most prevalent dopant for $Al_xGa_{1-x}N$. However, as the aluminum composition increased (x>0.45), the donor ionization energy of silicon increases well beyond room temperature thermal activation energies ($E_d > 0.025$ eV). In addition, silicon doping can influence the epitaxial $Al_xGa_{1-x}N$ growth mode, which results in the changes of the morphology and defect profile. Changes in growth mode affect the maximum carrier density due to the increase in defect level concentration, such as deep donor levels. In addition, high aluminum concentration induces strain in epitaxially deposited films which may result in cracking. As a result, the MOCVD process must be optimized to maximize doping and minimize strain. We here report a systematic study of the silicon doping effects in high-mole fraction $Al_xGa_{1-x}N$, including correlation of morphology and defect density. Atomic force microscopy (AFM) and electron microscopy results will be presented and correlated to silicon doping levels. Cathodoluminscence (CL) measurements were performed to relate the intensity of the deep-level luminescence with the band-edge intensity. Typical capacitance-voltage (C-V) measurements of show concentrations in the range of $1x10^{18}$ cm^{-3} across a 50 cm diameter $Al_xGa_{1-x}N$ epitaxial layer with Al concentration of x=0.54. Results from high mole fraction $Al_xGa_{1-x}N$ doping experiments and UV opto-electronic devices based on these epitaxial layers will be presented.

Y10.2
Modulation N Doping of AlGaN for Improved Deep UV LEDs. Jianping Zhang, Hongmei Wang, Zheng Gong, Ming Su, Shuai Wu, Vinod Adivarahan, Maxim Shatalov, Ashay Chitnis, Changqing Chen, Wenhong Sun, Jinwei Yang, Grigory Simin and M. Asif Khan; EE, Univ. SC, Columbia, South Carolina.

At present the key performance limiter for state-of-the-art deep ultraviolet light-emitting diodes (UV LEDs) is the relatively poor material quality and the doping efficiency of the n- and p-type AlGaN. In the past we have utilized AlN/AlGaN superlattice and pulsed atomic layer epitaxy (PALE) grown ultrahigh-quality AlN buffers to improve the structural quality and reduce the defects in such AlGaN layers. We now report a study of n- and p-type modulation doping of high Al-content AlGaN layers for deep UV LEDs. Two modulation doping schemes were studied: the first, a delta (d) doping where monolayers of the Si(Mg) dopant were inserted in the bulk AlGaN layers, and the second, where modulation doped (Si(Mg):AlN/AlGaN)m multiple layers were used. The Si-d-doping was found to be very effective in reducing the etch pits (threading dislocations). For an Al0.5Ga0.5N layer the etch pit density reduced to 108 cm-2 from the starting value of over 109 cm-2. However, the superlattice modulation doped (Si:AlN/Al0.5Ga0.5N)m layers exhibited the highest Hall mobility and structural quality as measured by the symmetric/asymmetric scans of high-resolution x-ray diffraction (XRD). At a doping level higher than 1018 cm-3, the (Si:AlN/Al0.5Ga0.5N)m layer had a room-temperature Hall mobility of 125 cm-2/v.s; full width at half maximum (FWHM) values of 2.7 and 5.8 arcmins for the XRD (002) and (114) rocking curves, respectively. Our new modulation-doping scheme also results in excellent hole-conduction in p-type AlGaN layers with Al-content up to 30%. For an Al0.3Ga0.7N layer we measured a room temperature hole concentration of 1.1e17 cm-3 and a mobility of 8 cm2/v.s. We will discuss the growth, and electrical and optical characterization results. Improvement in the deep UV LED performance from the use of modulation-doping schemes will also be presented.

Y10.3
Deep UV stimulated emission by electron-beam pumping of bulk AlGaN alloys. A Bhattacharyya[1], T C Chen[1], J Cabalu[1], T D Moustakas[1], J R Smith[2], Deepak K Sengupta[2], Randolph E Treece[2], J I Pankove[2] and W F Hug[3]; [1]Electrical Engineering, Boston University, Boston, Massachusetts; [2]Astralux Incorporated, Boulder, Colorado; [3]Photon Systems, Inc, Covina, California.

In the development of electrically pumped deep UV emitters based on the III-Nitride family, the stumbling block has been the difficulty in effectively doping p-type AlGaN alloys with relatively high AlN mole

fraction. An alternative approach is to employ an electron-beam as an excitation source. Electron-beam pumped blue lasers based on InGaN MQWs and employing cleaved facets to form an in-plane laser cavity have already been reported in the literature. In this paper we investigate single-pass surface mode optical emission from bulk AlGaN alloys and AlGaN/AlN MQWs upon e-beam excitation at room and low temperatures. AlGaN bulk films with AlN mole fraction varying from 30% to 90%, and AlN/AlGaN MQWs have been grown by plasma assisted Molecular Beam Epitaxy. The films were characterized by X-Ray Diffraction and optical absorption studies to ascertain the alloy composition as well as to determine the presence of long-range atomic ordering in these materials. Electron-beam excitation studies at room and low temperature were conducted in a JEOL scanning electron microscope system fitted with an Oxford Research Cathodoluminescence setup. Our results indicate that the luminescence for AlGaN alloys with a high AlN mole fraction exhibit a red-shift of as much as 30 nm compared to the absorption edge. This may be partly due to the strong long-range atomic ordering exhibited in these materials as indicated by XRD studies. We demonstrate e-beam pumped stimulated emission at temperature 100K from bulk 72% AlGaN alloy centered at 273nm in a single-pass surface emission mode, without the use of an external cavity. Evidence is provided by a nonlinear increase of the luminescence intensity by five orders of magnitude for an increase in the electron-beam current by a less than three orders of magnitude. Correspondingly a narrowing of the luminescence peak from 16 to 4 nm has been observed. Our evidence is that the threshold current is about 100A/cm^2

Y10.4
Optically Pumped UV AlInGaN MQW Laser at 340 nm.
Yiping He[1], Yoon-Kyu Song[1], A. V. Nurmikko[1], Maria Gherasimova[2] and J. Han[2]; [1]Division of Engineering, Brown University, Providence, Rhode Island; [2]Electrical Engineering, Yale University, New Haven, Connecticut.

We have demonstrated an optically pumped room temperature pulsed laser at 340 nm, based on a separate confinement AlInGaN MQW heterostructure design. The photoluminescence spectrum on the as-grown wafer material showed dominant emission near 340 nm, with a spectral linewidth of approximately 15 nm. Samples were fabricated for edge emission by dry etching parallel end facets to form cavities of varying length from 1- 2.5 mm. Optically pumped lasing was achieved by using a pulsed laser at 308 nm wavelength at threshold peak power of approximately 300-500 kW/cm2, about a factor of 3-5 higher than typically achieved in InGaN MQW violet optically pumped case. Apart from a well-defined threshold, the lasing was characterized by narrowing of the edge emission to about 2 nm with well defined (sub 0.1 nm linewidth) cavity modes present, as we all as a more than 100:1 intensity ratio in the TE/TM polarization. These results, coupled with amplified spontaneous emission spectroscopy on cavity-free samples provide a window on gain characteristics for the AlInGaN MQW system which can be helpful in pursuing a diode laser in the 340 nm and shorter wavelength regime. Research supported by DARPA SUVOS program under SPAWAR Systems Center Contract No. N66001-02-C-8017.

Y10.5
Emission Mechanisms in UV Emitting GaN/AlN Multiple Quantum Well Structures.
Madalina Furis[1], Alexander N. Cartwright[1], Hong Wu[2] and William J. Schaff[2]; [1]Electrical Engineering, University of Buffalo, Buffalo, New York; [2]Electrical Engineering, Cornell University, Ithaca, New York.

The need for efficient UV emitting semiconductor sources has prompted the study of a number of heterostructures of III-N materials. In this work, the temperature dependence of the photoluminescence (PL) properties of UV-emitting GaN/AlN multiple quantum well (MQW) heterostructures were investigated in detail. In all samples studied, the structure consisted of 20 GaN quantum wells, with well widths varying between 7 and 15 Angstroms, clad by 6nm AlN barriers, grown on top of a thick AlN buffer that was deposited on sapphire by molecular beam epitaxy. The observed energy corresponding to the peak of the emission spectrum is in agreement with a model that includes the strong confinement present in these structures and the existence of the large built-in piezoelectric field and spontaneous polarization present inside the wells. The observed emission varies from 3.5 eV (15 Angstrom well) to 4.4 eV (7 Angstrom well). Two activation energies associated with the photoluminescence quenching are extracted from the temperature dependence of the time-integrated PL intensity. These activation energies are consistent with donor and acceptor binding energies and the PL is dominated by recombination involving carriers localized on donor and/or acceptor states. Moreover, the temperature dependence of the full width at half-maximum (FWHM) of the PL feature indicates that inhomogeneous broadening dominates the spectrum at all temperatures. For the 15 and 13 Angstrom wells, we estimate that the electron-phonon interaction is responsible for less than 30% of the broadening at room temperature. This broadening is negligible in the 9 Angstrom wells over the entire temperature range studied. Moreover, well width fluctuations are primarily responsible for the inhomogeneous broadening, estimated to be of the order of 250meV for half-a-monolayer fluctuation in well width.

Y10.6
High-brightness vertical-structure InGaN light-emitting diodes with reflective p-contacts fabricated on Au substrates.
Ho Won Jang and Jong-Lam Lee; Dept. Materials Science and Engineering, POSTECH, Pohang, Gyungbuk, South Korea.

There has been tremendous interest in developing GaN-based light-emitting diodes (LEDs) for solid-state lighting. GaN-based white LEDs could replace conventional light bulbs. These GaN devices are commonly fabricated on sapphire substrates. For the devices on sapphire substrates, all contacts must be made from the top side, resulting in high spreading resistance and increased operating voltages. Furthermore, the poor thermal conductivity of sapphire prevents efficient heat dissipation, inhibiting device performance. Laser lift-off (LLO) techniques have been demonstrated to transfer GaN thin films from sapphire onto conducting substrates. But GaN films separated by LLO commonly suffer thermal and/or mechanical cracking. Thus the area of successfully separated GaN is typically below 1 cm^2. Here we present an innovative process by which GaN thin films can be easily transferred from original sapphire substrates onto Au substrates without cracking, resulting in high-brightness ultra-thin vertical-structure (UTVS) InGaN LEDs. UTVS LEDs have many advantages over conventional lateral-structure (LS) LEDs such as a large emitting area, no light absorption from semitransparent p-contacts, uniform current spreading, a short path of light propagation, and a low thermal resistance. The forward voltage of 300 μm^2 UTVS LEDs is ~3.1 V at 20 mA. With backside p-contact of high reflection (> 90 %), the light extraction efficiency (~80 %) is ~2 times higher compared to conventional LS LEDs. Thermal resistance is evaluated to be 1.8 W/K for the UTVS LEDs and 40.2 W/K for the LS LEDs. We expect that the UTVS LEDs could enable the production of high-power white LEDs replacing conventional light sources. Fabrication process flow, high reflective p-contacts, and device performance of the UTVS LEDs will be discussed.

Y10.7
Electroluminescence study of InGaN/GaN green LEDs with quantum dot active layers.
Jhang Woo Lee, Jae Ho Song and Young Gu Kim; Information and Communications, K-JIST, Gwangju, South Korea.

We investigated the injection and recombination characteristics of InGaN/GaN LEDs by using the electroluminescence (EL) measurements in the temperature range of 10-300K. Photoluminescence (PL) spectra were also obtained for the comparison. The selected LEDs have InGaN/GaN quantum well or dot structured active layers emitting green light. The EL spectra obtained with a low injection condition (<1mA) exhibit the unexpectedly large energy shift as much as 0.16eV from 2.5eV at 10K to 2.34eV at 300K. The 160meV EL shift is much larger than the PL energy shift, which is only 50meV from 2.41 to 2.36eV. More surprisingly, the EL peaks shift abruptly at 120K from 2.36 to 2.5eV, while the PL peaks shift gradually over the temperature range. This result indicates that there exist two localized energy states between which a sudden carrier transfer arises at 120K. We believe that the quantum dot active layer provides such dual energy states. The EL spectrum line width increases also abruptly at 120K to the maximum of 0.19eV from the 0.11-0.12eV elsewhere, but the PL line width rather decreases at the temperature to the minimum of 0.13eV from 0.15-0.17eV elsewhere. The EL spectra clearly show that around 120K injected carriers are evenly distributed to the two localized energy states. The EL data were compared with the other EL data obtained from the InGaN/GaN quantum well LED. It is clear that the quantum dot LED is more effective to confine the injected carriers due to the multiple energy states. We estimated the radiative efficiencies using the PL lifetime data. Combining these data with the EL spectrum data, we will calculate the injection efficiencies at various bias conditions and attempt to propose the optimum quantum dot active layer structure yielding a high efficient emission.

Y10.8
Overcoming the Far UV Cutoff in GaN Detectors for Visible Blind Imaging.
Robert A Beach, Shouleh Nikzad and Eric Jones; Jet Propulsion Lab, Pasadena, California.

Ultra thin optical windows were explored for improving the band width of back-illuminated GaN based UV detectors. Wide bandgap semiconductors, such as GaN and AlGaN, can potentially have high UV sensitivity comparable to modified Si photodiodes with the visible rejection ratio of solar-blind detectors, such as photocathode/micro channel plate combination imagers. A major limitation of current

AlGaN/GaN PIN detectors is their high energy cutoff due to absorption in the n-AlGaN optical window. We are developing high efficiency detectors operating from GaN band gap out to deep UV (365-250nm) by using alternatives to thick AlGaN optical windows. Diodes with >30% external QE were fabricated and characterized that showed moderate decrease in efficiency out to 250nm. The effects of buffer layer and n layer thickness on device performance are discussed, and a method for extending detector performance to higher energies is presented.

Y10.9
Persistent photocurrent in GaN Schottky ultraviolet detectors. Oded Katz, Gad Bahir and Joseph Salzman; Electrical Eng., Technion, Haifa, Israel.

GaN based Schottky detectors provide high response and low noise at UV wavelengths. Although typical photovoltaic detectors should ideally not exhibit gain, the presence of gain has been reported in by many researchers [‎1-3], and a model for it was recently proposed [4‎], by which gain originates from repopulation of interface traps, and the consequent recovery of the Schottky barrier. The saturation of the responsivity at high optical power [‎2-3], and the persistent photoconductivity (PPC), widely reported for GaN based optoelectronic devices [‎5], are two related effects arising from a non-ideal semiconductor crystal. The transit rise and decay currents associated with PPC show non-exponential time dependencies. Although, it is commonly acceptable that PPC is related to defect states or traps, no accurate physical model has been proposed to explain this temporal behavior. We have implemented GaN based Schottky detectors and measured their photoresponse as a function of the incident power, and time. The measured photoresponse show gain saturation and PPC behavior as depicted above. We present a microscopic model of the gain mechanism to explain these observations. Further, we extract physical properties, such as trap density at the semiconductor-metal interface and their trapping lifetime, from our measurements. Finally, we connect the fitting parameters of the stretch-exponential, to the device physical properties. 1. O. Katz, V. Garber, B. Meyler, G. Bahir, and J. Salzman, Appl. Phys. Lett. 80 (3), 347 (2002) 2. E. Monroy, F. Calle, E. Munoz, and F. Omnes, Appl. Phys. Lett. 74 (22), 3401 (1999) 3. D. Walker, E. Monroy, P. Kung, J. Wu, M. Hamilton, F.J. Sanchez, J. Diaz and M. Razeghi, Appl. Phys. Lett. 74 (5), 762 (1999) 4. O. Katz , V. Garber, B. Meyler, G. Bahir, and J. Salzman, Appl. Phys. Lett., 79 (10), 1417 (2001) 5. J.C. Carrano, T. Li, P.A. Grudowski, C.J. Eiting, R.D. Dupuis, and J.C. Campbell, J. Appl. Phys. 83 (11), 6148 (1998)

Y10.10
Design and fabrication of GaN-based light-emitting diodes with enhanced lateral light extraction. Hyunsoo Kim, Jaelee Cho, Hye Jeong Oh, Jeong Wook Lee, Sukho Yoon, Cheolsoo Sone and Yongjo Park; Samsung Advanced Institute of Technology, Yongin, Gyeonggi-do, South Korea.

We have designed and fabricated GaN-based light-emitting diodes (LEDs) with enhanced light extraction efficiency. For the efficient light extraction from the LED chip, it is more desirable to extract the traveling light toward lateral direction since the light of the lateral portion is much more than that of the vertical portion by about 3 times. In this regard, we designed LED chip with a number of holes acting as lateral exits for light extraction. These holes were fabricated from fine patterning by conventional photolithographic technique and selective dry etching. It was interesting to note that the mesa etching depth played an important role in changing the extraction efficiency. This could be explained by relationships between the critical angle (law of Snell) and lateral device geometry. Based on the optimized design, the LED chip showed the improved light output efficiency by 23 %.

Y10.11
Reduction of dark current in AlGaN/GaN Schottky barrier photodetectors with a low-temperature-grown GaN cap layer. Gou-Chung Chi[1], Jinn-Kong Sheu[1], Min-Lumn Lee[2], Yan-Kuin Su[2], Shou-Jinn Chang[2], Wei-Chi Lai[2] and Wen-Jen Lin[3]; [1]Department of Physics, National Central University, Chung-Li, Taiwan; [2]Institute of Microelectronics and Department of Electrical Engineering, National Cheng Kuhg University, Tainan; [3]Materials & Electro-Optics Research Division, CHUNG-SHAN INSTITUTE OF SCIENCE & TECHNOLOGY, Lung-Tan, Tao-Yuan.

AlxGa1-xN is one of the most promising materials for the fabrication of high-sensitive visible-blind ultraviolet (UV) detectors, since it has a large direct bandgap energy (3.41~6.2eV at room temperature). In the past few years, AlGaN-based UV photodetectors(PDs) with high performance have been demonstrated using different device types, such as p-i-n PDs, Schottky barrier PDs and metal-semiconductor-metal (MSM) photodetectors. Compared with bipolar PDs, the fabrication process of Schottky barrier PDs is much easier. The response speed of Schottky barrier PDs is also faster. However, leakage current in Schottky barrier PDs is also higher due to the large thermionic emission current in Schottky barrier PDs, as compared to the diffusion current in bipoloar junction PDs for a given applied voltage. To reduce the leakage current in Schottky barrier PDs, we deposited an low-temperature-grown GaN(LT GaN) layer, which has ultra-high resistivity(>10$\hat{9}$ Ω?/cm$\hat{2}$?), on top of undoped AlGaN layer to fabricate a AlGaN/GaN Schottky barrier PDs with low dark current. In other words, we have prepared GaN/i-Al0.27Ga0.73N/LT GaN/Ni/Au (sample A) and GaN/i-Al0.27Ga0.73N/Ni/Au (sample B) Schottky barrier ultraviolet (UV) photodiodes (PDs). Current-voltage measurements of the sample A showed a dark current as low as 20 pA at a reverse bias of 5V. It was found that we could significantly reduce leakage current and achieve a much larger photocurrent to dark current contrast ratio by introducing a LT GaN on top of the conventional nitride-based UV PDs. With incident light wavelength of 320 nm and a reverse bias of 1V, it was found that the measured responsivity was around 0.03 A/W and 0.015 A/W for sample A and sample B, respectively. Furthermore, it was found that the spectral responsivities in sample B showed a significant bias-dependent behavior, which might be due to the surface states. More optical and electrical properties of the fabricated PDs will be reported.

Y10.12
Proposal to Use GaAs(114) Substrates for Improvement of the Optical Transition Probability in Nitride Semiconductor Quantum Wells. Mitsuru Funato, Yoshinobu Kawaguchi and Shigeo Fujita; Electronic Science and Engineering, Kyoto University, Kyoto, Japan.

This paper demonstrates that the optical transition probability in nitride quantum wells can be drastically improved by the use of GaAs(114) substrates. The practically applied light emitting diodes and laser diodes are basically c-oriented strained quantum wells (QWs), and therefore, they experience a strong electric field due to the piezo polarization. Since the piezo electric field disturbs carrier recombination and, as a consequence, reduces the optical transition probability, it is important to reduce the piezo electric field to achieve a higher emission efficiency. In order to find a way to do so, we calculated the variations of the piezo electric field and the transition probability as a function of the tilt of the c-axis. The calculation was essentially the same as Jpn. J. Appl. Phys. 39, p.413 (2000), but here the spontaneous polarization was also taken into account. The InGaN/GaN single QW was chosen as a model structure because InGaN/GaN QWs are the basic device structure. In the calculation, it was assumed that GaN thickness was infinite, that GaN was perfectly relaxed, and that a 3-nm-thick InGaN well was grown coherently. The calculation showed that the electric field was maximum in c-oriented QWs, while that was 0 MV/cm when the tilt of the c-axis was about 40 or 90 degrees. Consequently, the optical transition probability was maximum at a tilt of about 40 and 90 degrees and minimum at 0 degree (c-oriented QW). This tendency was almost independent of the In composition. It is, thus, concluded that optical devices with a c-axis tilted by 40 or 90 degrees can promisingly show an improved device performance. So far, we have investigated the MOVPE growth of GaN on GaAs(11n) substrates (n = 1, 2, 3, 4, 8), and found that the superior structural and optical quality was obtained on the (114) substrate [APL79, p.4133 (2001)]. Much more interestingly, the c-axis of GaN grown on GaAs(114) is tilted by 30 degrees. This tilt angle is not equal to 40 degrees, at which the electric field is 0MV/cm as described above, though is expected to realize weak electric field, compared with a tilt of 0 degree. As a matter of fact, our calculation for 3-nm-thick InGaN/GaN QWs with an In composition of 20% showed that the electric field in the c-oriented QW was 2.6MV/cm, while that in the QW grown on GaAs(114) was 0.6MV/cm, which led to a 15 times larger optical transition probability in the QW on GaAs(114). This characteristic may also allow us to expand the emission wavelength range by increasing the In composition in InGaN wells on GaAs(114) without serious degradation of the transition probability, which is often observed in the conventional c-oriented QWs.

Y10.13
Manipulation of Spontaneous Polarization Fields in III-Nitrides. Andreas Buchholz, Sandra Lahmann, Uwe Rossow and Andreas Hangleiter; Institute of Technical Physics, Technical University of Braunschweig, Braunschweig, Germany.

Group-III-nitride semiconductors are being intensively studied for applications in light emitting devices as well as in high-power high-frequency electronic devices. Recently, it has been recognized that the latter requires precise control over surface and interface charges, which are intimately related to the strong piezoelectric and spontaneous polarization fields present in the wurtzite nitrides. We have studied nitride heterostructures and their surfaces using electron stimulated desorption in an UHV environment. Our samples were

as-grown GaInN/GaN and GaN/AlGaN single and multiple quantum well structures grown by low-pressure MOVPE in a horizontal reactor (AIX 200RF). Utilizing the quantum well luminescence excited by the electron beam as a probe inside the sample, we are able to derive the internal electric field both locally and globally from the emission peak energy and the Fabry-Perot (FP) fringes, respectively. We observe dramatic metastable changes of the emission intensity upon electron irradiation. From the change in refractive index derived from FP fringes and the linear electro-optic coefficient we are able to derive the electric field deeply inside the sample, reaching values in excess of 3 MV/cm, consistent with theoretical predictions for the spontaneous polarization field. Our observations suggest that screening of spontaneous polarization is based on charged species at the surface which be removed by electron stimulated desorption.

Y10.14
Abstract Withdrawn

Y10.15
Current-Voltage and Reverse Recovery Characteristics of Bulk GaN p-i-n Rectifiers. Yoshihiro Irokawa[1], B. Luo[2], Jihyun Kim[2], J. R. LaRoche[2], F. Ren[2], K. H. Baik[3], S. J. Pearton[3], C. -C. Pan[4], G. -T. Chen[4], J. -I. Chyi[4], S. S. Park[5] and Y. J. Park[5]; [1]Toyota Central Research and Development Laboratories, Inc., Nagakute, Japan; [2]Department of Chemical Engineering, University of Florida, Gainesville, Florida; [3]Department of Materials Science and Engineering, University of Florida, Gainesville, Florida; [4]Department of Electrical Engineering, National Central University, Chung-Li, Taiwan; [5]Samsung Advanced Institute of Technology, Suwon, South Korea.

There is a strong interest in the development of wide bandgap semiconductor power rectifiers for use in inverter units in hybrid electric vehicles or power utility switching. P-i-n rectifiers are expected to have larger reverse blocking voltages than Schottky rectifiers, but inferior switching speeds due to stored charge and higher forward turn-on voltages. However, for very high blocking voltage (> 3 kV) or forward current densities (> 100 A·cm^{-2}), the p-i-n rectifier is expected to have the advantage because of the prohibitive lenkage and resistance of the drift region in a Schottky diode. All of the GaN p-i-n rectifiers reported to date have been heteroepitaxial devices, with the active layers grown on Al_2O_3 substrates. In this study, p-i-n rectifiers were fabricated on epitaxial layers grown on free-standing GaN substrates, and the current-voltage (I-V) and reverse recovery switching characteristics of bulk GaN p-i-n rectifiers were performed. The forward turn-on voltage, V_F was ~5 V at 300 K and displayed a positive temperature coefficient. The specific on-state resistance (R_{ON}) was ~5 mΩ·cm2 at 300 K, with an ideality factor of ~2 and activation energy for low forward current density of ~1.6 eV. This is consistent with carrier recombination in the space charge region via a mid-gap deep level. The figure-of-merit, V_B^2/R_{ON}, where V_B is the reverse breakdown voltage, was 0.32 MW·cm^{-2}. The reverse recovery time was ~ 600 ns at 300 K. The improved forward characteristics relative to previous heteroepitaxial p-i-n GaN rectifiers show the advantages of employing a GaN substrate to make a true vertical transport geometry device. These devices appear very promising for high power switching application.

Y10.16
GaN/AlGaN HEMTs Grown by Hydride Vapor Phase Epitaxy on AlN/SiC Substrates. J R LaRoche[1], B Luo[1], F Ren[1], K H Baik[2], D Stodilka[2], B Gila[2], C R Abernathy[2], Stephen J Pearton[2], Yuri Melnik[3], Alexei Pechnikov[3], Vitali A Soukhoveev[3], Vladimir A Dmitriev[3], C C Pan[4], G T Chen[4] and J I Chyi[4]; [1]Department of Chemical Engineering, University of Florida, Gainesville, Florida; [2]Department of Materials Science and Engineering, University of Florida, Gainesville, Florida; [3]TDI, Inc, Silver Spring, Maryland; [4]Dept. of Electrical Engineering, National Central University, Chung-Li, Taiwan.

GaN/AlGaN High Electron Mobility Transistors (HEMT's) were fabricated on layer structures grown by metal organic chemical vapor deposition (MOCVD) on AlN-on-SiC templates. The templates were fabricated by growing thick (from 20 to 50 microns) AlN layers by hydride vapor phase epitaxy on 6H-SiC substrates. The presence of the AlN provides an insulating buffer for effective inter-device isolation, producing isolation currents in the 10-9 A range. These initial HEMTs exhibit saturated drain source current of > 400 mA/mm with maximum transconductance of > 70 mS/mm. The devices show lower degrees of current collapse relative to more conventional HEMTs fabricated on sapphire substrates, suggesting that the lower defect density is beneficial in reducing surface state trap concentration. This approach has great potential for reducing the cost of high quality HEMT structures.

Y10.17
Electronic Properties of a Two-Dimensional InN Substitution Layer Embedded in GaN. Bachir Bouhafs[1], Abdelaziz Lakdja[1] and Pierre Ruterana[2]; [1]Department of Physics, University of Sidi Bel Abbes, Sidi Bel Abbes, Algeria; [2]LERMAT, FRE 2149 CNRS, ENSICAEN, Caen, France.

InN/GaN (001)-superlattices with one isovalent atomic substitution layer can be regarded as perfectly InGaN ordered alloys. Owing to their efficient optical excitonic transitions, the extreme case of atomic substitution layers in the active region is expected to play a crucial role for the next generation optical devices. In this paper, we show how the modification of the optical properties of InN/GaN depends on the chemical and size effects associated with the embedded InN substitution layer. Using a first-principles method, we investigate the electronic and optical properties of a two-dimensional InN substitution layer embedded in GaN. The present calculations are based on 'state-of-the-art' DFT-LDA using the self-consistent full potential linear augmented plane wave method within the local-density functional approximation. The InGaN alloy is known as an 'anomalous' alloy because large composition-dependent bowing coefficients and new defect levels appearing in the band gap of GaN have been observed experimentally. We will show theoretically that InN/GaN shows some band structure anomalies in the lower conduction band region.

Y10.18
Substrate effect on aging for AlGaN/GaN HFET epiwafers grown by MOCVD. Ronald Birkhahn, David W Gotthold, Shiping Guo, Brian Albert, Doru Florescu, Dong Lu and Boris Peres; Corporate R&D, Emcore, Somerset, New Jersey.

AlGaN/GaN heterostructure field effect transistors (HFETs) are envisioned for use in a range of high power, high frequency amplifier applications. Concurrent to improvements in the materials properties and device designs for these AlGaN HFETs, reliability of the packaged amplifiers is being investigated to establish the long-term viability of these materials. In order to increase the piezoelectric doping for greater speed and higher power operation, researchers continually push the limits of this materials system to achieve smoother interfaces, higher Al compositions, and thicker barriers. Until recently, all the reliability research has been on devices, but recent work at Emcore has revealed significant long term aging effects that occur in the AlGaN epitaxial material, without any device processing. Over a time period ranging from days to months, the sheet resistance of the as-grown wafers slowly increases from < 400Ω/ to as high as 5000Ω/. It is clear that the overall AlGaN strain, as determined by Al content and barrier thickness, is the primary factor in determining epitaxial material lifetime, however many other parameters (i.e. capping layers, substrate polish, substrate quality) appear to have an effect on the degradation rate. We have previously studied and determined stable HFET structures on SiC fall within $Al_xGa_{1-x}N$ barriers of $x \leq 0.3$ and thickness $\leq$ 23 nm. In this presentation, we will compare the stability of the AlGaN HFETs grown on SiC to comparable structures on sapphire and Si substrates. While the long-term stability of this material is still in question, initial results show less aging on sapphire and Si. After a period of >90 days, the AlGaN HFETs on sapphire have not aged while those on SiC have completely failed.

Y10.19
X-ray Diffraction Analysis of Threading-Dislocation Density in GaN-Based HEMTs. Allen West[1,2], Stephen Lee[1], Andrew Allerman[1], Karen Waldrip[1], David Follstaedt[1] and Cammy Abernathy[2]; [1]Sandia National Laboratories, Albuquerque, New Mexico; [2]Materials Science and Engineering, University of Florida, Gainesville, Florida.

The device performance of GaN-based HEMTs is limited by the high dislocation density associated with GaN films grown heteroepitaxially on SiC. Threading dislocations in the GaN limit mobility by scattering electrons in the HEMT conductive channel. In this study, we develop improved x-ray diffraction (XRD) methods for measuring the threading-dislocation density in GaN; we then apply these methods to the analysis of GaN-based HEMTs. The XRD analysis measures the characteristic width for a series of GaN Bragg peaks. Symmetric (0002), (0004), and (0006) reflections, as well as asymmetric (10-11) and (20-22) reflections are used. The tilt variance, the twist variance, and the lateral coherence length of the GaN epilayer are extracted from the measured peak widths using a reciprocal-space model that describes the (hkl) dependence of the convolved peak-width contributions. Threading-dislocation densities are then estimated from the XRD measurements of tilt, twist, and coherence length using two separate methods. The first method proceeds using the tilt and twist variances and the classic formulation of Dunn and Koch. The second method proceeds by assuming that the measured coherence length equals the rms spacing of randomly arranged threads. For selected samples, the threading-dislocation density determined by XRD is benchmarked against transmission electron microscopy; good agreement is found. The validated XRD

technique is used to measure the threading-dislocation density in ten different HEMT heterostructures, which have room-temperature mobilities ranging from 327 cm2/V-s to 1830 cm2/V-s. Correlation of the dislocation-density measurements with the HEMT-mobility data clearly shows that the mobility decreases with increasing dislocation density. We find that room temperature mobilities >1800 cm2/V-s require threading dislocation densities <1x10E9 cm-2 in the GaN channel. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the Department of Energy under Contract DE-ACO4-94AL85000.

Y10.20

Wafer-fused n-AlGaAs/p-GaAs/n-GaN Heterojunction Bipolar Transistors with Base-Collector Setback.

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Recently we reported the first AlGaAs-GaAs-GaN heterojunction bipolar transistor (HBT), a device that might combine the high-breakdown voltage of an n-GaN collector with the high mobility of an AlGaAs-GaAs emitter-base.[1] Because the high degree of lattice mismatch between GaAs (lattice constant of 5.65A) and GaN (3.19A) precludes an all-epitaxial formation of this device, we formed the GaAs-GaN heterostructure via wafer fusion, also called direct wafer bonding. The conduction band offset of the wafer-fused GaAs-GaN heterojunction is unknown. However, a positive offset is likely, given the electrical characteristics and low current gain observed in our previous work.[2] The effective conduction band offset may be due to fusion-induced traps or defects, or to the natural conduction band offset between GaAs and GaN regardless of the fusion process. This presentation will describe new HBT structures, modified to counteract a likely conduction band spike. Our new HBT structures have a reduced base thickness of 100 nm and an n-GaAs base-collector setback layer of two different thicknesses (20 or 50 nm). A setback layer should shift the fused GaAs-GaN interface slightly into the collector. By decreasing the barrier in the conduction band at the base-collector junction, these new structures may increase collector current and hence current gain. Gummel plots and common-emitter I-V characteristics will be presented. Additionally, simulated energy band diagrams suggest alternative improvements for the HBT materials structure. Possibilities include the addition of a Si delta-doped layer at the collector side of the fused junction, the use of a lightly doped p-GaAs (rather than n-GaAs) base-collector setback, and the use of a higher band-gap setback material such as AlGaAs. References: [1] Sarah Estrada, Huili Xing, Andreas Stonas, Andrew Huntington, Umesh Mishra, Steven DenBaars, Larry Coldren, and Evelyn Hu, Applied Physics Letters 82 (5), 820-2 (2003). [2] Accepted for publication: Sarah Estrada, Andrew Huntington, Andreas Stonas, Huili Xing, Umesh Mishra, Steven DenBaars, Larry Coldren, Evelyn Hu, Applied Physics Letters 83 (3), (tentatively scheduled July 21, 2003). First author's contact information: estrada@engineering.ucsb.edu http://sarah.optimism.us/engineering/

Y10.21

Design and Fabrication of GaN-Based Permeable Base Transistors.

Jasper Cabalu[1], Anirban Bhattacharyya[1], Ian Friel[2], Yuri Fedyunin[1], Enrico Bellotti[1], Theodore Moustakas[1], Vittorio Camarchia[3], Michele Goano[3], Liberty Gunter[4] and Kanin Chu[4]; [1]Department of Electrical and Computer Engineering, Boston University, Boston, Massachusetts; [2]Department of Physics, Boston University, Boston, Massachusetts; [3]Dipartimento di Elettronica, Politecnico di Torino, Torino, Italy; [4]BAE SYSTEMS, Nashua, New Hampshire.

The permeable base transistor (PBT) is a viable alternative to the current generation of planar GaN based devices for RF power amplifier applications. PBTs are essentially vertical MESFETs that can be fabricated with equivalent gate lengths shorter than 0.10 μm. Although PBTs have already been demonstrated in Si, GaAs and SiC, to date there is very little being done to develop these devices in the III-Nitride material system. In this work we present an integrated approach to the design and fabrication of PBTs on GaN that includes both physics based simulation and submicron device growth and processing. The performance of several device structures have been simulated using a microscopic physics based model that include the detail of the GaN electronics structure. A simpler model based on an energy balance technique has also been developed for production design. For PBTs with feature size of 0.2 μm the model predicts a maximum transconductance of 500 mS/mm and f_T=70GHz. Electro-thermal simulations have been performed to determine the device performance in realistic operational conditions. We also present the fabrication technique of an etched grooved GaN-based permeable base transistor structure. Starting from an n-type GaN layer structures grown by Halide Vapor Phase Epitaxy (HVPE), the device active layers are deposited using Molecular Beam Epitaxy (MBE). The fabrication process takes advantage of isolations pads via He implantation and submicron etching of the collector fingers. The finger/groove dimension is < 0.2 μm and with a 1:1 and 1:3 pitch that have been obtained by e-beam lithography. Several device structures have been fabricated and characterized. The current-voltage characteristics will be presented and compared to the simulation results. Preliminary RF performance results will be also illustrated.

Y10.22

Correlation of Transport and Structural Properties in AlGaN/GaN HEMT Structures grown with AlN Interlayers.

Marianne Germain[1], Maarten Leys[1], Steven Boeykens[1], Wouter Ruythooren[1], Dominique Schreurs[1], Khang-Hoon Choi[1], Gustaaf Borghs[1], Benny Van Daele[2], Gustaaf Van Tendeloo[2], Jean-Louis Farvacque[3] and Francesca Carosella[3]; [1]MCP, IMEC, Leuven, Belgium; [2]EMAT, University of Antwerp, Leuven, Belgium; [3]USTLille, Lille, France.

Strain state of the GaN layer close to the interface in AlGaN/GaN HEMT structures has direct influence on the electrical properties of the 2DEG, as well on the structure of the top AlGaN layer, on which contacts are formed. Strain engineering is made possible by the growth of AlN interlayers (IL), deposited at low temperature (LT), in the buffer GaN. HEMT structures, only differing by the number of LT AlN IL in the buffer GaN, have been grown by LP MOVPE on sapphire. The top AlGaN layer was always grown with a thickness of 30 nm and an Al content of 33%. The AlN interlayers were grown to thickness of 20 nm and their separation was 240 nm. The Van-der-Pauw sheet resistivity,at room temperature is greatly reduced by the presence of interlayers: from 700Ω/Sq in the reference sample to 500Ω/sq for the samples with 1 and 3 interlayers and down to 340Ω/Sq in the sample with 2 interlayers. Magneto-transport measurements show very clear Shubnikhov-de-Haas oscillations at a magnetic field of 2.5 T at 1.5 K (sample with three interlayers), showing a better quality than that of the reference sample. TEM investigation of the samples shows that all the threading dislocations propagating through the GaN layer are stopped at the GaN/AlN interface. Although new dislocations are generated at the AlN/GaN interface, their directions are not parallel to the c-axis and they annihilate. Thus, the threading dislocation density is reduced from 6.10^9 cm^{-2} in the reference sample to approximately $1.10^9 cm^{-2}$ after only one interlayer. AFM measurements showing cracking of the surface AlGaN layer on the reference sample grown without any interlayers, also demonstrate that this cracking is drastically reduced by the presence of interlayers. HRXRD measurements show two GaN related peaks, indicating different strain states of GaN. From electrical measurements, and confirmed by TEM, the optimum number of interlayers is two. Interesting correlation of electrical and structural characterization is moreover observed between transport and AFM measurements. Recent theoretical simulations of the mobility versus carrier density have shown that the introduction of some electrical roughening of the surface is necessary to explain the mobility drop observed at high electron concentration in HEMT structures. Correlation between structural and electrical behaviour will be discussed, in relationship with theoretical simulations of the transport properties. HEMT devices have also been processed: values for I_{dmax} are up to 1 A/mm. Good pinch-off of the devices processed from samples containing interlayers could be achieved at a voltage of -7 V.

Y10.23

AlGaN/GaN/AlN Heterostructure Field Effect Transistors with Highly Resistive AlN Epilayers.

Zhaoyang Fan, Mim Lal Nakarmi, Jingyu Lin and Hongxing Jiang; Department of Physics, Kansas State University, Manhattan, Kansas.

AlGaN/GaN heterostructure field effect transistors (HFETs) are still facing some major problems. One is the current dispersion phenomenon, related with the bulk defects trapping and surface states of the heterostructure; the insufficient pichoff caused by the low resistive GaN bulk layer is another challenge. Here we propose and demonstrate a novel AlGaN/GaN/AlN HFET with highly resistive AlN epilayer grown on sapphire substrate. The characterization of the fabricated HFET device and the numerical simulation of the related structure are reported. With the highly resistive AlN replacing the GaN bulk layer, the parasitic conduction in the bulk layer is completely removed and leakage current is reduced; at the same time, the large conduction band edge discontinuity between GaN channel and AlN layer limits the spill-over of channel electrons into the bulk, diminishing the current dispersion related with bulk trapping. Simulation shows that the adverse effect to channel electrons caused by the negative polarization charge between GaN and AlN interface can be overcome by optimizing the structure and adoption of backside doping. DC characterization of the fabricated devices on sapphire substrate with 1 μm gate length shows high saturation current (>1 A/mm), excellent gate control ability with pinch-off voltage −6 V, and a maximum transconductance of 180 mS/mm. Even without

passivation, the device shows small current dispersion (< 10%) under 1 μs pulse gate driving.

Y10.24

Photoluminescence and X-Ray Diffraction Study of AlGaN-GaN HEMT Structures for Microwave Electronics.

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A custom-built multi-wafer metalorganic chemical vapor deposition reactor has been developed for the epitaxial growth of (Al,In)GaN-based high electron mobility (HEMT) structures on silicon carbide substrates. Gas flow modeling guided the development of the reactor design to minimize composition and thickness variability of deposited films. Real-time in-situ chemical sensing of precursors, adducts, and byproducts was used to optimize the quality of AlN, GaN, and AlGaN films and to ensure reproducibility of the deposition process. Multiple HEMT structures were grown on 4H- and 6H-SiC to establish the role of substrate and film properties as sources of HEMT performance variability. The structural, optical, and electrical properties of the substrate, nucleation layer, and buffer layer were measured by several techniques, including x-ray diffraction (XRD), x-ray reflectivity (XRR), photoluminescence (PL), and Hall effect. Additionally, high-resolution maps of AlGaN composition and thickness were generated. Correlations between the measured properties of the substrate and films with HEMT performance metrics such as I_{MAX}, f_T, transconductance, output resistance, and breakdown voltage will be reported. It was found that the material properties best correlated with the electrical performance were substrate rocking curve linewidth, PL emission intensity, and AlGaN-GaN interface roughness (measured by XRR). While samples in this study with differing defect microstructure and impurity content yielded devices with an I_{MAX} value greater than 1 A/mm, other key parameters such as breakdown voltage and output resistance were significantly affected by material variation.

Y10.25

Contactless Characterization of GaN/AlGaN High Electron Mobility Transistor Structures Using Surface Photovoltage Spectroscopy.

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GaN/AlGaN high electron mobility transistors (HEMT) structures have been characterized using surface photovoltage spectroscopy and empirical modeling. The two oppositely directed electric fields in the GaN buffer and AlGaN Schottky layer define the potential profile of the HEMT structure. The sensitivity of SPV to electric field direction makes it possible to distinguish between signals coming from different regions of the structure. Numerical simulations show that the total surface photovoltage (SPV) is a combination of two signals from the buffer and Schottky layer regions. In a GaN/AlGaN HEMT structure, a triangular quantum well (QW) is formed at the interface with the Schottky layer. Thus, holes generated by absorption at the QW are swept toward the Schottky layer, contributing to a dominant positive signal in the QW region of absorption. The doping level n together with the surface charge density Qsur define the distribution of the vertical electric fields within the device and the electron sheet density in the channel. Numerical simulations show the effect of n and Qsur on the spectrum. A statistical approach and the Design of Experiment technique enables developing an empirical model, which correlates spectrum features with n and Qsur. This model enables comparing SPV spectra of different structures and extracting differences in charge densities. Comparison of two different GaN/AlGaN epi-structures shows dQsur =2.1x1012 cm-2, indicating different surface defect densities. Surface passivation of HEMT structures significantly affects the device performance. Thus, it is crucially important to study its influence on device surfaces. Applying the model for comparison of the spectra of a HEMT structure before and after passivation yields a numerical value of dQsur=1.8x1012 cm-2. In addition, the signal drop of the AlGaN in the passivated structure starts at higher energy values. This is probably due to passivated surface states present in the AlGaN prior to SiN deposition.

Y10.26

LP-MOCVD growth of GaAlN/GaN heterostructures on Silicon Carbide. Application to HEMT's devices.

di Forte-Poisson Marie-Antoinette[1], Magis Michelle[1], Tordjman Maurice[1], Romann Annick[1], Aubry Raphael[1], Delage Sylvain[1], di Persio Jean[2], Grimbert Bertrand[3] and Gaquiere Christophe[3]; [1]advanced Electron Device Department, Thales Research&Technology, Orsay, France; [2]Universite de Lille, Villeneuve d, France; [3]IEMN, Villeneuve d, France.

Wide Band Gap semi-conductors, such as SiC and GaN, exhibit many attractive properties : the combination of the large band gap, high breakdown field (over 2MV/cm) and the ability to form high quality heterostructures in GaAlN/GaN with good transport properties, make these wide band gap materials ideal candidates for high power, high frequency application. In this paper, we report the LP-MOCVD growth optimisation of GaAlN/GaN heterostructures on Silicon Carbide substrates for HEMT applications and the first device performances with these structures. GaAlN/GaN heterostructures with 22% Al content were grown in a single wafer Aixtron reacteur, on semi-insulating on-axis 4H SiC substrates, using Triethylgallium (TEG), Trimethylaluminium (TMA), and ammonia (NH3) as group III and group V precursors. The critical impact of some growth parameters on the physical properties of the GaAlN/GaN epilayers, has been identified. The SiC substrate surface preparation (Ex-situ and In-situ surface preparation), the GaN nucleation layer growth conditions (growth temperature, layer thickness, strain) appeared to be key steps of the GaAlN/GaN/SiC growth. GaAlN/GaN HEMT structures under study consisted of 1micrometer insulating GaN buffer layer followed by a 27nm Si doped GaAlN layer with 22% Al content and an undoped GaN cap layer, 3nm thick. A specific design of the GaN buffer layer has been optimised in order to obtain insulating material. This was confirmed by a background doping lower than 10E14 cm-3 and a very low leakage current (I< 2pA at -20V). The transport properties of such heterostructures were studied as a function of temperature from 300K to 10K. Hall mobility higher than 1000cm2V-1s-1 has been obtained at 300K associated with a sheet carrier density of 1.2 10E13 cm-3.The high mobility obtained at low temperature (3600cm2V-1s-1 at 77K) for the mentioned HEMT structures reveals a good quality of the GaAlN/GaN interface which was confirmed at the atomic scale by TEM measurements. Other characterisation techniques such as AFM, HR-XRD, C-V measurements and sonogauge have been applied to investigate the material quality of the GaAlN/GaN HEMT structures. AFM and HR-XRD measurements evidenced a very good crystalline quality of the GaAlN/GaN epilayers with a RMS close to 0.3nm, and a rocking curve FWHM[0002] lower than 80 arcsec related to the GaN layer. The device fabrication was performed using a conventional mesa isolated process with RIE for mesa definition. Ti/Al/Ni/Au was used for ohmic contact formation and Pt/Au for the gate metal. The devices were realized with gate length (Lg) of 0.8micrometers, 0.5micrometers, 0.3micrometers and 0.15micrometers. The first devices measured at 10GHz using a load pull system exhibit CW ouput Power in excess of 2.8W/mm for a gate length of 0.5micrometers. Under static measurements we found a maximum drain current Idss around 1A/mm and a good pinch-off voltage of -5V.

Y10.27

MOCVD Growth of AlGaN/GaN HEMT Structures on 100mm Substrates.

David William Gotthold, Brian Albert, Ronald Birkhahn, Shiping Guo and Boris Peres; EMCORE, Somerset, New Jersey.

AlGaN/GaN High electron mobility transistors (HEMTs) have attracted a great deal of attention in recent years because of their promise for high performance RF devices and high temperature operation. A great deal of research has already been done on these devices using small (50mm) substrates. However, growth on larger substrates is important due to both the high cost of processing wafers and the limited availability of narrow linewidth lithography equipment needed for high performance devices. EMCORE is currently developing growth on 100mm sapphire and silicon substrates in order to understand the issues involved in growth on large substrates and to speed the development of epitaxy on 100mm SiC once such substrates become available. Because of the significant lattice and thermal mismatches on all substrates, as well as the extreme growth conditions used for GaN epitaxy, scaling wafer size is not as straight forward as in other compound semiconductor technologies. Wafer bowing, thermal variations, and strain all significantly effect uniformity, repeatability, and device performance. Using a variety of in-situ characterization tools, these effects can be studied and controlled through structure and process improvements. On 100mm silicon substrates, HEMT structures have been grown with a sheet resistance of 360Ω/ and uniformity < 3% across the wafer.

Y10.28

In-situ chemical sensing for real-time prediction of material quality and film thickness in GaN MOCVD.

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Maryland.

Gallium nitride promises to be a key material for future semiconductor devices aimed at high frequency, high power electronic applications. Manufacturing for such high performance products will require systematic methods to achieve reproducible metrics such as material quality and film thicknesses in multilayer structures. In a joint project between the University of Maryland and Northrop Grumman Corporation, we have anticipated this challenge and addressed it to accelerate learning at the R&D stage through the use of in-situ mass spectrometry. Employed as a real-time, in-situ chemical sensing technique in the MOCVD process, real-time mass spectrometry reveals the generation of by-product species due to the deposition reaction as well as background/impurity species in the process. By-product signals provide a real-time predictor of the crystal quality of the material, as determined post-process by ex-situ XRD (x-ray diffraction), with the mass-spec/XRD correlation exhibiting an average uncertainty of 5% or less. Background impurity levels in the gas phase were also closely correlated to post-process, ex-situ photoluminescence measurements for material quality. In addition, time-integration of the by-product signals through the deposition process cycle provides a thickness metrology suitable for controlling the thickness of the individual layers in the GaN-based HFET structure. These applications of real-time, in-situ chemical sensing, as predictors of material quality and film thicknesses, promise significant benefits in terms of rapid learning in R&D and advanced process control in GaN-based semiconductor manufacturing.

Y10.29
Growth of Bulk-like GaN Layers in a Vertical HVPE Reactor. Carl Hemmingsson, Henrik Larsson, Daniela Gogova and Bo Monemar; IFM, materials science, Linkopings university, Linkoping, Sweden.

2-inch crack free GaN single crystal layers with a thickness up to 0.6 mm have been grown by hydride vapour phase epitaxi (HVPE) in a vertical hot-walled reactor at atmospheric pressure. The growth was performed in a mixture of gallium chloride and ammonia in the temperature range 1050-1100 0C with nitrogen as a carrier gas. The process gases are distributed from the bottom upwards through the reactor. Thus, the substrate is exposed downwards to the process gases. Using this rector geometry, growth rates up to 250 μm/hr have been obtained. The growth process has been studied concerning the choice of template, pre-treatment and initial growth process. Several different substrates, both buffered and unbuffered, have been used in the investigation. The structural and optical properties of the layers have been studied using optical microscopy, X-ray diffraction (XRD) and low temperature photoluminescence (LTPL). The result shows that the interface region between the template and the GaN single crystal layer and the uniformity of the layer thickness is important in order to obtain stress-relaxed layers. Thus, in order to achieve thick crack free GaN layers of high crystalline quality an optimised reactor geometry, template pre-treatment, and initial growth process is necessary.

Y10.30
Multi-Step Optimization Of Cantilever Epitaxy for Improved Material Quality. Christine C. Mitchell, Daniel D Koleske, David M Follstaedt, Nancy A Missert, Paula P Provencio, Andrew A Allerman and Michael E Coltrin; Sandia National Laboratories, Albuquerque, New Mexico.

Cantilever epitaxy (CE) has been developed by our group to produce GaN on sapphire with low dislocation densities as needed for improved devices. A mechanism is employed to manipulate dislocations, which normally propagate vertically from the buffer layer to the surface, to turn them into the plane of the material. This technique has allowed us to achieve densities as low as 5 x 10^7/cm^2 averaged across multiple posts, overgrowth zones, and coalescence fronts on sapphire cantilever epitaxy substrates, as determined with AFM, TEM and cathodoluminescence (CL). This density is one to two orders of magnitude below that of conventional planar growths. These improvements suggest that large-area devices, such as LEDs, can be fabricated on these low defect density substrates. Recent work has been completed to eliminate a defect type seen in early cantilever epitaxy attempts, labeled as "dark-block defects" because they are non-radiative and appear as dark rectangles in CL images, and a repeatable method has been established for coalescing large areas of cantilever epitaxy material without these defects. Characterization with SEM, AFM, and TEM of cantilever material in defect areas indicates that the defects result from misorientations between the two cantilever sections being brought together. Examination of the evolution of the cantilever films for many growths, both partial and complete will be presented and the importance of controlling the growth conditions and crystal morphology at multiple steps will be emphasized.

Y10.31
Abstract Withdrawn

Y10.32
Lateral overgrowth of patterned SiC substrates by GaN and AlGaN. Uwe Rossow, U Ahrend, N Riedel, D Fuhrmann, F Hitzel, M Greve and A Hangleiter; Inst. f. Techn. Physik, TU Braunschweig, Braunschweig, Germany.

The large defect densities associated with heteroepitaxial growth of group-III nitrides are detrimental particularly to laser diodes. Well-known lateral growth schemes such as epitaxial lateral overgrowth (ELOG) rely on overgrowth of pre-deposited nitride layers applying dielectric masks. However, in order to avoid contaminations and simplify the processes it is advantageous to separate growth process and pattern formation. We have developed a patterning process for n-type doped SiC substrates based on photoelectrochemical (PEC) etching. Stripe patterns aligned along either [1-100] or [11-20] directions, respectively, and periods between 5 and 10 microns were etched to depths between 0.5 and 2 microns. Low-pressure metal-organic vapor phase epitaxy (MOVPE) in a horizontal reactor was then used for overgrowth. We have previously shown that a defect reduction by this approach is possible and found an improvement by a factor of 5-10 compared to optimized growth on planar substrates. A further reduction requires more insight in the facet formation and stability. We performed growth experiments varying growth temperature, V/III ratio and total pressure. A defect reduction requires low pressures compared to growth on planar substrates. For 50mbar and V/III ratios of 2500 lateral-to-vertical growth rates of more than 8 were found. A further reduction of pressure had no significant effect. We found instabilities for extreme V/III ratios of more than 5000. Here screw dislocation most likely originating at the substrate interface seem to be the cause. We find that in our growth environment facets of low angles between 18 and 30degs are surprisingly stable. We are presently investigating the nature of these facets which need to be avoided in order to efficiently reduce the defect density.

Y10.33
Migration Enhanced Metal Organic Chemical Vapor Deposition for III-N Heterostructure Growth. Qhalid Fareed[1], Remis Gaska[1], Michael Shur[2] and Asif Khan[3]; [1]Sensor Electronic Technology, Inc., Columbia, South Carolina; [2]Department of ECSE and Broadband Center, Rensselaer Polytechnic Institute, Troy, New York; [3]Department of EE, University of South Carolina, Columbia, South Carolina.

We report on a new Migration Enhanced Metal Organic Chemical Vapor Deposition (MEMO-CVD) epitaxial technique for growth of AlN/GaN/InN films and heterostructure layers. MEMO-CVD is an improved version of Pulsed Atomic Layer Epitaxy (PALE), which deposits quaternary AlxInyGa1-x-yN layers by repeats of a unit cell grown by sequential metal organic precursor pulses of Al-, In-, Ga- and NH3. In PALE, the duration of each pulse in the unit cell is fixed, and the NH3 pulse always followed each metalorganic pulse. In MEMO-CVD, the duration and waveforms of precursor pulses are optimized, and, generally speaking, the pulses overlap allowing for a continuum of growth techniques ranging from PALE to conventional MOCVD. MEMO-CVD combines a fairly high growth rate for buffer layers with reduced growth temperature (by more than 150 C) and improved quality for active layers. Using this new technique, we achieved a better mobility of pre-cursor species on the surface and, thus, better atomic incorporation l and improved surface coverage. This enabled scale up of our epitaxial technology to four inch and allowed for precise growth of Strain and Energy Band Engineered structures resulting in elimination of aging effects in AlGaN/GaN heterostructures grown on large area substrates.

Y10.34
Growth and Characterization of Epitaxial GaN Thin Films on 4H-SiC (1120) Substrates. B. P. Wagner[1], Z J Reitmeier[1], E A Preble[1], D N Zakharov[2], Z Liliental-Weber[2] and R F Davis[1]; [1]Materials Science, North Carolina State University, Raleigh, North Carolina; [2]Lawrence Berkeley National Laboratory, Berkeley, California.

GaN thin films were grown via organo-metallic vapor phase epitaxy on a-plane 4H-SiC (11$\bar{2}$0) substrates using an AlN buffer layer. High-resolution x-ray diffraction confirmed that the GaN deposited epitaxially in the same orientation as the substrate. The average on-axis x-ray full-width half-maximum of the (11$\bar{2}$0) reflection was 331 arcsec. Atomic force microscopy images show that the microstructure of the AlN buffer layer and the subsequently deposited GaN have a highly oriented growth structure where parallel growth features propagate in the [1$\bar{1}$00] direction. No surface features were resolved using scanning electron microscopy imaging and the interfaces between the substrate, buffer layer, and epi-layer were

continuous. Plan-view transmission electron microscopy analysis showed stacking fault and threading dislocation densities to be $\sim 1.6 \times 10^{6}$ cm^{-1} and $\sim 3.3 \times 10^{10}$cm^{-1}, respectively.

Y10.35

Investigation of the Thermal Properties of GaN Grown on Silicon Substrates. Christian Mion[1], Yun-Chorng Chang[1], John Muth[1] and Jeff Brown[2]; [1]ECE Dept, North Carolina State University, Raleigh, North Carolina; [2]Nitronex Corporation, Raleigh, North Carolina.

One of the principle problems of high power electronic devices is the extraction of heat from the active region of the device. The thermal conductivity of the substrate is a crucial parameter affecting the thermal dissipation capability of a device. In this study we investigated the thermal conductivity at room temperature of 7 GaN and AlGaN/GaN layers grown on silicon, employing the 3 omega thermal conductivity method. By varying the thickness of the GaN layers from 0 to 700 nm on silicon substrates the interfacial resistance between the GaN and Silicon substrate was shown to be very small. The thermal conductivity for the GaN layers was found to range from 130 to 140 W/mK which is comparable to thermal conductivity of the silicon substrate. In device quality films consisting of a 30nm AlGaN layer on GaN, the effective thermal conductivity of the device layers was found to increase by about 10% to 156 W/mK. This result indicates that the heat transfer of GaN on silicon is as good as either GaN or silicon alone, and that no thermal degradation attributable to the GaN/Silicon interface is observed.

Y10.36

Growth of high qulity crack-free GaN on AlN quantum dots over Si(111)substrates by MOCVD. Wenhong Sun[1], Jingli Chen[2], Lianshan Wang[1] and S. J. Chua[1]; [1]Optoelectronics and Photonics, IMRE, Singapore, Singapore; [2]Departemt of Materials Science, NUS, Singapore, Singapore.

Si as a substrate material for GaN growth promises two advantages. First, the well known cleaning and other technological procedures developed for Si can be used. Second, the substrate can be chemically removed in order to get self supporting GaN templates for further growth. Therefore GaN grown on Si is of great interest despite the large misfit. Most research work has been done on the growth of GaN on Si substrates, and high-bright GaN LEDs have been successfully fabricated from the subsequent structural materials. Due to the large differences in the thermal extension coefficient and lattice constants between GaN and Si substrates, the cracks on the surface of GaN epilayers usually can hardly avoidable. As we know, the buffer layer is important for the quality of GaN on either Sapphires or Si substrates. To improve the material quality even without any cracks, research workers have employed many kinds of buffer on Si substrates, such as SiC, AlO and GaAs ect. In this study, AlN self-assembled quantum dots (QDs) with a high density of $\sim$ 4.4 X1010/cm2 on Si(111) substrates have been grown by low-pressure chemical vapor deposition (using Emcore D125 system) under a very low V/III ratio of 350. We found that using AlN-QD/AlN buffer high quality 2" GaN epilayers without cracks were grown even when the epilayer thickness reached to 3 micro. The successful growth of the large area crack- free GaN over Si substrates can be attributed to the stain relaxation by the underlying AlN QDs. The quality and morphology were investigated by atom force microscopy, transmission electron microscopy, high resolution X-ray diffraction and optical microscope.

Y10.37

Lateral Overgrowth of in situ SiN Masks for Low Dislocation Density GaN on Sapphire. Till Riemann[1], Juergen Christen[1], Zsolt Makkai[2], Bela Pecz[2], Eric Frayssinet[3], Bernard Beaumont[3], Jean-Pierre Faurie[3] and Pierre Gibart[3]; [1]Institute of Experimental Physics, Otto-von-Guericke-University, Magdeburg, Germany; [2]Research Institute for Technical Physics and Materials Science, Hungarian Academy of Sciences, Budapest, Hungary; [3]Lumilog, Vallauris, France.

For GaN growth on foreign substrates, a strong reduction of dislocation density is possible by masking techniques, e.g. Epitaxial Lateral Overgrowth (ELO) or Pendeo Epitaxy. However, these techniques suffer from *exsitu* lithography steps. Additionally, highly defective coalescence boundaries, which are typical for these methods make device technology difficult. An alternative approach [1] involves *insitu* SiN micro-masking, which completely eliminates these problems and, if properly optimized, leads to similar results as for state-of-the-art ELO material. We present Ultra Low Dislocation density (ULD) GaN layers obtained by Metal Organic Vapor Phase Epitaxy (MOVPE). For these layers, siliconnitride is *insitu* deposited prior to the growth of the low temperature GaN buffer on sapphire substrate, leading to amorphous SiN islands of 20-40 nm lateral extension and 20nm height. This process induces a 3D nucleation at the early stages of GaN growth and is comparable with an ELO process on a random mask pattern. Cross-sectional spectrally resolved Cathodoluminescence Microscopy (CL) clearly visualizes a self-organized growth mechanism similar to two-step ELO on stripe masks. The initial part of the MOVPE sample, which corresponds to lateral growth and coalescence of the randomly distributed GaN islands, exhibits a weak peak due to the acceptor-bound exciton and dominant, slightly broadened (D^0X) emission (FWHM=4 meV), which is also characteristic for the laterally grown regions of standard MOVPE-ELO. As in ELO, a strong lateral bending of threading dislocations (TDs) is visible in CL and directly evidenced by Transmission Electron Microscopy (TEM). Following the transition from lateral to overall (0001)-growth, the upper part of the GaN layer exhibits sharp (D^0X) luminescence (FWHM(2.5 meV) and a significant contribution of the free exciton, proving its excellent optical quality. At the sample surface, the TD density is well below 10^8 cm^{-2} for 10μm thick layers as independently measured by Atomic Force Microscopy, CL, and TEM. [1] S. Haffouz, H. Lahrèche, P. Vennégues, B. Beaumont, F. Omnès, and P. Gibart, Appl. Phys. Lett. 73, 1278 (1998).

Y10.38

Effects of Misorientation and Step Treatment of Sapphire Substrate on the Electronic Properties of AlGaN/GaN Heterostructures. Seongwoo Kim[1], Toshimasa Suzuki[1] and Kazuhiro Haga[2,1]; [1]System Engin., Nippon Institute of Technology, Miyashiro, saitama, Japan; [2]Technical Div., CHICHIBU FUJI Co., Ltd., Ogano, Saitama, Japan.

AlGaN/GaN field effect transistors (FETs) had recently been attracting much attention because of their promising uses for high-voltage, high-power, and high-temperature microwave applications. We report the growth and characterization of AlGaN(30nm)/GaN(3μm) heterostructures grown simultaneously on three types of sapphire substrates in a multi-wafer rotating disc low-pressure MOCVD system (EMCORE D-125). Three substrates were used, one of which was exact c-plane sapphire, the rest two were misoriented 0.15° from the c-plane sapphire with and without step treatment. X-ray diffraction (XRD) measurement indicated that the Al composition of all three samples was 15%. X-ray rocking curves (XRC) for both symmetrical and asymmetrical reflections were applied to evaluate the crystal quality of AlGaN/GaN heterostructures. The FWHM values of symmetrical (002) reflection did not show significant difference. On the other hand, those of asymmetrical (102) reflections decreased from 604 arcsec for c-plane sapphire to 557 arcsec for misoriented 0.15°, and to 530 arcsec for step-treated. Scanning laser microscopy (SLM) was used to observe small pits, which seemed to be corresponded to the threading dislocations of AlGaN/GaN heterostructures. The density of the pits on c-plane sapphire, on misoriented 0.15° and on step-treated were $1.2X10^8$, $1.1X10^8$ and $8.3X10^7$ cm^{-2}, respectively. Finally room temperature Hall-effect measurement was performed to measure the electron mobility. The electron mobility on c-plane sapphire was 1200 cm^2/Vs and that on misoriented 0.15° substrate was increased to 1400 cm^2/Vs. The electron mobility on step substrate was further improved to as high as 1550cm^2/Vs. Sheet carrier density for this sample was $8.0X10^{12}$cm^{-2}. As a summary, it was found that misorientation and step treatment decrease the density of threading dislocation improving crystallinity of AlGaN/GaN heterostructures, resulting in the higher electron mobility.

Y10.39

MOCVD AlGaN/GaN HFET'S Material Optimization and Devices Characterization. Alexander V. Demchuk, Don Olson, Dan Olson, Minseub Shin and Gordon Munns; APA Optics, Inc., Blaine, Minnesota.

A novel buffer layer structure has been investigated in order to improve the planarity and to reduce the defect densities at the channel of an AlGaN/GaN heterostructure field effect transistor (HFET). This method employed multi-AlN buffer layers and intermediate AlGaN/GaN superlattices. A custom built, inductively heated low-pressure MOCVD system has been used to growth highly uniform AlGaN/GaN heterostructure on (0001) sapphire or 6H-SiC (0001) two-inch substrates. Grazing incidence x-ray reflection (GIXRR) was used to evaluate the planarity of the channel heterointerface. These results were compared with atomic force microscopy (AFM) results and etch pit density studies of the material and confirm a consistent, significant improvement in the root mean squared (RMS) surface roughness when this method is employed. Devices on both sapphire and silicon carbide have been grown and processed. Hall measurements of samples grown on sapphire substrates yielded mobilities as high as 2100 cm2/Vs at the sheet carrier density (ns) of 1.0x1013 cm-2 and 2250 cm2/Vs and ns=1.2x1013 cm-2 on silicon carbide substrates accordingly. A significant dependence in the mobilities and carrier density on the growth temperature has been revealed. The trend likely reflects changes in the planarity of the heterointerface directly related to the

growth temperature. The DC characteristics of the devices showed transconductances above 200 mS/mm for a gate length greater than 2 microns. Results on shorter gate length devices also will be presented.

Y10.40

Epitaxial growth of group III nitrides on silicon substrates via a reflective lattice-matched zirconium diboride buffer layer. John Tolle[2], Radek Roucka[1], Cole Ritter[2], Peter Crozier[3], Andrew Chizmeshya[3], Ignatius Tsong[1] and John Kouvetakis[2]; [1]Physics and Astronomy, Arizona State University, Gilbert, Arizona; [2]Chemistry and Biochemistry, Arizona State University, Tempe, Arizona; [3]Center for Solid State Science, Arizona State University, Gilbert, Arizona.

Growth of metallic and reflecting ZrB_2 films is conducted on Si(111) substrates at 900 °C using a single-source unimolecular precursor $Zr(BH_4)_4$ in a molecular-beam epitaxy chamber. Epitaxial growth of ZrB_2(0001) is accomplished despite the very large lattice mismatch between ZrB_2 and Si(111). High-resolution cross-sectional transmission electron microscopy images of the sharp ZrB_2/Si(111) interface show a heteroepitaxial relationship involving a "magic mismatch" of coincidence lattices. The GaN films grown on the ZrB_2/Si(111) template is virtually homoepitaxy because of the very small lattice mismatch, 0.6 %, between the in-plane lattice parameters of ZrB_2(0001) and GaN(0001). The reflective nature of ZrB_2 surface presents an added advantage to optoelectronic applications of the III nitrides grown on Si.

Y10.41

Arsenic Incorporation Behavior in Nitrogen-rich GaNAs Alloys Synthesized by Metalorganic Chemical Vapor Deposition (MOCVD). Maria Gherasimova[1], R. G. Wheeler[2], J. Han[1], L. J. Guido[3], K. L. Chang[4] and K. C. Hsieh[4]; [1]Electrical Engineering, Yale University, New Haven, Connecticut; [2]Applied Physics, Yale University, New Haven, Connecticut; [3]Materials Science and Engineering, Virginia Tech, Blacksburg, Virginia; [4]Electrical and Computer Engineering, University of Illinois, Urbana, Illinois.

Group III-nitride alloys with mixing on the anion sublattice, such as GaNAs, recently attracted considerable attention. Theoretical predictions of direct band gap over the entire composition range, combined with anticipated deep band offsets, make these materials desirable for a number of potential optoelectronics applications. Successful incorporation of nitrogen in GaAs matrix and isoelectronic doping of GaN with arsenic have been demonstrated and studied by several groups. On the other hand, higher levels of arsenic incorporation in nitrogen-rich GaNAs are less thoroughly investigated due to a significant miscibility gap in the GaNAs system. In the present work, homogeneous GaNAs alloy films containing 3 to 4 percent of arsenic anion fraction were grown on GaN templates by MOCVD at 700 C. Composition and structure of the films were characterized by electron probe microanalysis (EPMA), transmission electron microscopy (TEM), and x-ray diffraction (XRD). Some of the ternary GaNAs films were subjected to a post-growth annealing at 1000 C in nitrogen ambient and compared to as-grown material. Due to the metastable nature of GaNAs ternary, annealing resulted in the precipitation of binary GaAs inclusions of several nanometers in size embedded in the nitrogen-rich GaN(As) matrix. These quantum dot features were observed by the cross-sectional TEM imaging, and identified by the characteristic GaAs peaks in the transmission electron diffraction patterns. On the other hand, as-grown GaNAs films exhibited no evidence of binary phase segregation. Band gap reduction due to alloying was observed by the optical transmission measurements, leading to an estimate for the bowing parameter of 25 eV in the films with the arsenic content of 3.5 % - in keeping with the theoretical prediction of Bellaiche et al. (Phys. Rev. B v. 54, p. 17568 (1996)) of a significant degree of band gap bowing in nitrogen-rich GaNAs alloys.

Y10.42

A study of the elemental interdiffusion in GaN/Si wafer grown by metalorganic vapor phase epitaxy. Xianfeng Chen[1], Masayasu Ishiko[1], Yousuke Kuroiwa[2] and Nobuhiko Sawaki[2]; [1]Toyota Central R&D Labs. Inc., Nagakute-cho, Japan; [2]Nagoya University, Nagoya.

In order to fabricate high qualified photonic and electric devices based on GaN/Si material with vertical structure, a good understanding of the hetero-interfaces, especially the epitaxial film/Si interface, in the wafer is necessary. Secondary ion mass spectrometry (SIMS) investigation on GaN/n-Si samples grown by metalorganic vapor phase epitaxy (MOVPE) reveals a temperature dependence of interdiffusion at the epitaxial film/substrate interface. Increasing growth temperature will increase the penetration depth of high Al concentration region in the substrate, which might result in an inadvertent junction in the n-Si. Photocurrent spectroscopy measurement on the sample shows, when a light with energy lower than the GaN bandgap is incident on the sample from the GaN side, a current flowing from the Si side to the GaN side occurs under zero bias voltage. It indicates that the hetero-epitaxy growth brings an internal electric field into the original uniformly doped n-type Si(111) substrate. The current direction decides that conduction band is bending upward at the epitaxial film/substrate interface in the silicon region, which is well consistent with the result of the elemental interdiffusion observed from SIMS measurement.

Y10.43

Growth and Characterization of AlN and GaN Thin Films Deposited with Al Pre-Flows on Si(111) Substrates. Z. J. Reitmeier and R. F. Davis; Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

AlN films and GaN films with AlN buffer layers were deposited on Si(111) substrates via metalorganic vapor phase epitaxy using varying times of Al pre-flows prior to AlN growth. Atomic force microscopy (AFM) was used to determine the influence of Al pre-flow time on the nucleation and surface morphology of the AlN and GaN films. When preceded by a 10 second Al pre-flow, AlN films feature an increased and more uniform nucleation density as compared to films deposited without Al pre-flows. Ten second Al pre-flows were also found to result in a reduction of the RMS roughness for 100 nm thick AlN films from 2.7 nm to 0.9 nm. AFM of 0.5 μm thick GaN films deposited on AlN buffers with varying pre-flow times showed reduced roughness and decreased pit density when using Al pre-flows of 10 or 20 seconds. High resolution x-ray diffraction of the GaN films showed a reduction in the average full-width half-maximum (FWHM) of the GaN (00.2) reflection from 1100 arcsec to 870 arcsec when the AlN buffer layer was initiated with a 10 second Al pre-flow. Increasing the pre-flow time to 20 seconds and 30 seconds resulted in average (00.2) FWHM values of 980 arcsec and 1570 arcsec respectively. Similar behavior of the peak widths was observed for the (30.2) and (10.3) reflections when the pre-flow times were varied from 0 to 30 seconds.

Y10.44

Effects of Cu-ion implantation into epitaxial (Ga,Al)N films grown by metalorganic vapor deposition. Zhe Chuan Feng[1], D. Mehta[1], Paul D. Helm[1], David Nicol[1], Ian Ferguson[1], Jayantha Senawiratne[2] and Nikolaus Dietz[2]; [1]Electrical & Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [2]Physics, Georgia State University, Atlanta, Georgia.

Ion implantation of copper into a variety of epitaxial GaN, AlN and AlGaN films grown on sapphire by Metalorganic Chemical Vapor Deposition (MOCVD) has been performed. Secondary ion mass spectroscopy (SIMS) data, similar to the theoretical simulation, showed the Cu-implants to have maximum concentration values of about 1E18 per cubic centimeter near 100 nm and continue to a depth beyond 350 nm with an implantation energy of 280 keV at both room temperature and 375 C. High resolution X-ray diffraction (HR-XRD), Raman, and Fourier transform infrared (FTIR) spectroscopy were used to characterize the crystalline damages and structural variation of nitrides due to Cu-implantation and the recovery from the subsequent high temperature (700-900 C) annealing. From XRD (0004) 2Theta-Omega pattern, Cu-implanted GaN exhibited an additional band at ~0.43 degree below the GaN (0004) peak, while it disappeared after rapid thermal annealing (RTA) at 700 C. Raman and FTIR data indicated amorphalization due to Cu-implantation, and crystalline structure recovery after RTA. UV-visible transmission measurements revealed two absorption bands in AlN due to Cu-implantation, located at ~ 1.5 and 2.8 eV below the AlN band edge absorption at 6.2 eV. An absorption band from Cu-implanted GaN and AlGaN (15%) is found at ~0.69 eV and ~0.73 eV, respectively, below their corresponding band gaps. Low temperature photoluminescence (PL) for Cu-implanted and annealed GaN showed the effect of crystalline damage due to the Cu-implantation and recovery of GaN features. The donor-acceptor pair (DAP) features are observed below 3.35 eV and their intensities are varied with the annealing temperature. Discussion is given in comparison with Cu-implantation into GaAs performed in early years.

Y10.45

Real-Time Optical Monitoring of InN Gas Phase Kinetics at Elevated Pressures. Nikolaus Dietz, Harald Born, Martin Strassburg and Vincent Woods; Physics & Astronomy, Georgia State University, Atlanta, Georgia.

Gaining insides in the growth kinetics of nucleation and coalescence of heteroepitaxial thin films is crucial for controlling a chemical vapor deposition process, since it defines the perfection of the heteroepitaxial film both in terms of extended defect formation and chemical integrity of the interface. The here presented research focuses on the real-time optical monitoring of gas phase- and surface chemistry processes during the heteroepitaxial nucleation and growth of InN layers on sapphire substrates. A high pressure chemical vapor deposition HPCVD reactor with integrated optical diagnostics to

monitor in real-time gas flow dynamics, gas-phase decomposition kinetics, and the film growth process itself, is used o study the growth process at elevated pressures from 1 bar up to 100 bar. These experimental data are of crucial importance to provide (a) input parameter for process models and simulation codes, and (b) establish growth parameter sets needed for analysis and control of chemical vapor deposition at elevated pressure. Data are presented for the optical methods of real-time process monitoring to analyze the initial stages of heteroepitaxy and steady-state growth in the different pressure ranges.

Y10.46

A Compositional, Structural, and Optical Study of HVPE and MOCVD $Al_xGa_{1-x}N$ Films Grown on Sapphire (0001) Substrates. Albert V. Davydov[1], William J. Boettinger[1], Lawrence H. Robins[1], Alexander J. Shapiro[1], Norman A. Sanford[2], Mohamed El Bouanani[3], Denis V. Tsvetkov[6], Vitali A. Soukhoveev[6], Stacia Keller[4], Umesh K. Mishra[4], Steven P. DenBaars[4], Christine Russell[5] and Simon Bates[5]; [1]MSEL, NIST, Gaithersburg, Maryland; [2]EEEL, NIST, Boulder, Colorado; [3]Dept. of Materials Science, University of North Texas, Denton, Colorado; [4]Electrical and Computer Engineering Dept., University of California, Santa Barbara, California; [5]Bede Scientific, Inc., Englewood, Colorado; [6]TDI, Inc., Silver Spring, Maryland.

A study was performed of compositional, structural, and optical properties of $Al_xGa_{1-x}N$ films grown by MOCVD and HVPE on (0001) sapphire. The Al mole fractions of the films were determined independently by EDS and by RBS compositional analysis. The 'a' and 'c' lattice parameters and the strain state were measured by high resolution X-ray diffraction. Stress-free values of the 'a' and 'c' lattice parameters were derived, and shown to have a non-linear dependence on Al fraction. The deviation from Vegard's law may be explained by the thermodynamics of the $Al_xGa_{1-x}N$ alloy system. Prism-coupled waveguide analysis, in conjunction with spectroscopic transmission/reflection, led to the derivation of Sellmeier equations for the ordinary refractive index (from 0.5 eV to the band gap) and extraordinary index (1.16 eV to 2.8 eV). The EDS and RBS data enable accurate correlation of the refractive index and other optical properties with Al fraction. Transmission/reflection and cathodoluminescence measurements show that the room temperature band gap has a nonlinear dependence on Al fraction, with a quadratic (bowing) parameter of approximately -1.3 eV. From comparison of room-temperature and low-temperature cathodoluminescence, the band gap increases by 0.05 eV or less from 298 K to 15 K. Large sample-to-sample variations were observed in the low-temperature CL lineshape, suggesting a strong influence of film growth conditions on alloy fluctuations, residual strain, and/or defect content.

Y10.47

Recombination Related to the Two-Dimensional Electron Gas of AlxGa1-xN/GaN Single Heterostructures Studied with Picosecond Time-Resolved Photoluminescence. Qing Yang[1,2], Rob Armitage[1,2], Jonathan Lim[1,2], Eicke R. Weber[1,2], Ronald Birkhahn[3], David Gotthold[3], Shiping Guo[3] and Brian Albert[3]; [1]Department of Materials Science and Engineering, University of California at Berkeley, Berkeley, California; [2]Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California; [3]Emcore Corporation, Somerset, New Jersey.

Near bandgap radiative recombination in unintentionally doped AlxGa1-xN/GaN (x=0.28 to 0.35) single heterostructures grown by metalorganic chemical vapor deposition is investigated using picosecond time-resolved photoluminescence. Hall effect measurements at 295K show both high sheet carrier concentrations ($\sim 10^{13}$ cm^{-2}) and high mobilities (804 to 1304 cm^2/Vs), suggesting the formation of a two-dimensional electron gas (2DEG) at the heterointerface. The luminescence decay of the 3.481 eV emissions at 11K, which are usually assigned to the donor-bound excitons in GaN, is composed of two stages that are separated for about 300 ps and with distinctly different decay lifetimes. In addition, the second stage is saturated at high excitation power and slightly red shifted with time. Samples of higher Al% also show luminescence in the spectral range of 3.44 eV to 3.45 eV with silimar slow capture and decay behaviors as the second stage of the 3.481 eV emission. The observed emissions are explained by recombination processes involving the 2DEG at the heterointerface.

Y10.48

Gain Characteristics of InGaN/GaN Quantum Well Structures with Various Silicon Doping Conditions. Yung-Chen Cheng[1], En-Chiang Lin[2], Hsiang-Chen Wang[1], C. C. Yang[1,2], Kung-Jen Ma[3], Chang-Chi Pan[4] and Jen-Inn Chyi[4]; [1]Inst. Electro-Optical Eng., National Taiwan University, Taipei, Taiwan; [2]Inst. Electronics Eng., National Taiwan University, Taipei, Taiwan; [3]Dept. Mechanical Eng., Chung Hua University, Hsinchu, Taiwan; [4]Dept. Electrical Eng., National Central University, Chungli, Taiwan.

Silicon doping in InGaN/GaN quantum wells (QWs) has been wildly used in fabricating high performance light emitting devices. With silicon doping, the effects of growth mode change, microstructure alternation, potential fluctuation reduction, strain relaxation, and piezoelectric field screening have been reported. However, most previous studies of silicon doping effects focused on the samples emitting purple-blue photons. Usually, it is difficult to achieve uniform InGaN alloy, particularly with high indium contents. This is so due to the solid phase immiscibility and phase separation, which stems from the large lattice constant mismatch between GaN and InN. In this paper, we report the characteristics of stimulated emission (SE) or gain, of high indium (in the green range) InGaN/GaN QWs. The results of relatively low-indium-content QWs were compared to show the effects of indium content variation. In our results, only the sample of high-indium and barrier doping shows the multi-peak SE feature that is quite different from previously reported. The SE spectra of the un-doped and well-doped samples of high-indium content show only two peaks. In the low-indium content samples, the SE peaks appear on the high-energy side of PL spectra that can be explained with the emission from the carriers confined in the localized states of indium-rich clusters. In our previous studies, it has been found that silicon doping in InGaN/GaN QWs could strongly affect the nano-structures. In particular, quantum-dot-like structures could be formed. Such a phenomenon was especially clear in barrier-doped samples. Therefore, we may interpret the multi-peak feature of SE in the high-indium barrier-doped sample as the contributions of quantized states in quantum dots of different sizes, compositions, or shapes. Hence, the observed peak merging behavior when temperature was raised can be explained as the re-distribution of thermal carriers among different energy levels and neighboring locations of different potential minima.

Y10.49

Novel Method for the Activation of Acceptor Dopant in AlN Introducing Localized Band by Isoelectronic Dopant. Toshiyuki Takizawa, Semiconductor Device Research Center, Matsushita Electric Industrial, Co., Ltd, Osaka, Japan.

Controlled p-type doping into nitride semiconductors is crucial for the development of optoelectronic devices. In this study we propose a novel method to activate acceptor dopant in AlN by introducing isoelectronic dopant, and have theoretically demonstrated using first-principles method. The acceptor dopant in AlN makes deep acceptor level (more than 100 meV) and generates few hole carriers into the valence band because of large affinity of N. On the other hand, incorporation with group-V isoelectronic dopant (P, As and Sb) that has small affinity compared with N into AlN makes localized band upward the valence band maximum (VBM), and its energy offset from VBM is higher than that of the acceptor level. When both acceptor dopant and isoelectronic dopant are incorporated into AlN, holes created by acceptor dopant can be easily activated by small affinity of isoelectronic dopant, and can move in the localized band. We have verified this novel p-type material, Mg-doped AlN:V (V=P or As), using first-principles pseudopotential method. 256 supecells are employed in this study. As a calculation result, incorporation of P (less than 6.25 %) and As (less than 1.56 %) makes localized band upward VBM of AlN, and moreover the energy offset of localized band approximately corresponds to VBM of GaN (-8.37 eV). The incorporation of acceptor dopant Mg into AlN:V decreases the Fermi level from -8.23 eV to -8.33 eV, whereas the conventional Mg-doped AlN still has a deep acceptor level. Accordingly hole concentration drastically increases in the localized band and can be effectively injected into VBM of GaN. Consequently novel p-type material, p-AlN:V, is very effective to inject hole current into VBM of GaN. The author acknowledges Prof. James S. Harris at Stanford University for use of first-principles programs.

Y10.50

In-situ real time characterizations of long-range and short-range surface morphology change during ion beam assisted epitaxy of GaN. Bentao Cui[1,2] and Philip I Cohen[2,1]; [1]CEMS, University of Minnesota, Minneapolis, Minnesota; [2]ECE, Univ of MN, Minneapolis, Minnesota.

Periodic patterns have been induced by low-energy ion bombardment [1]. In the current work, in-situ, real-time light scattering, combined with Reflection High Energy Electron Diffraction (RHEED), were used to study the evolution of the surface morphology of GaN during ion beam assisted MBE growth. Ga was provided by a thermal effusion cell; ammonia was used as the nitrogen source. A hot-filament Kaufman ion source was used to supply sub-KeV ion beams. Sapphire and MOCVD GaN templates were used as the substrates. A Desorption Mass Spectrometer (DMS) was used to calibrate the growth temperature. Before growing GaN, the sapphire substrates were pretreated in an ion flux and then annealed for cleaning. The sapphire surface was then nitrided in ammonia at 1100K for about 10

min. After nitridation, a thin GaN buffer layer was prepared by a sequence of adsorption and annealing steps. During the growth, the short-range surface morphology and film quality were monitored in situ by RHEED. In a real-time way, the long-range surface morphology was monitored in-situ by light scattering technique. Photodiode detector and CCD camera were used to record the reflected light scattering intensity and spectra profile respectively. A grating-patterned GaN was used first to study the ion-bombardment effects on periodic surface morphology. Preliminary results showed that the light scattering reflection beam intensity decrease when annealing at 950K. After 20 min 500 eV Ar ion bombardment from a glancing angle, the (01) reflection beam intensity increased by 50%, while the specular beam intensity decreased by 50%. Roughness parameters such as interface width, lateral correlation length, and the roughness exponent, can be extracted from the light scattering profiles and will be compared to that obtained from AFM. Partially supported by the National Science Foundation and the Air Force Office of Scientific Research. I. J. Erlebacher, M. J. Aziz, E. Chason, M. B. Sinclair, and J. A. Floro, Phys. Rev. Lett. 82, 2330 (1998); J. Erlebacher, M. J. Aziz, E. Chason, M. B. Sinclair, and J. A. Floro, Phys. Rev. Lett. 84, 5800 (2000)

Y10.51

Band offset measurements of the GaN(0001)/HfO2 interface.

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The use of HfO_2 or other high-k dielectrics as a passivation layer on GaN-based high voltage devices and as a gate insulator in field effect transistor (FET) devices requires knowledge of the band alignment of this interface. Photoemission spectroscopy has been used to observe the interface electronic states as HfO_2 was deposited on clean n-type Ga-face GaN (0001) surfaces. The HfO_2 was formed by repeated deposition of several monolayers of Hf metal followed by remote plasma oxidation, and a 650°C densification anneal. The as-grown GaN/HfO_2 interface showed an increase in upward band bending from the clean surface of 0.5 eV giving a type II valence band offset (VBO) of -0.1 eV. The 650°C anneal resulted in a ~0.5 eV change in band bending and band offset. The final annealed interface exhibited a type I VBO of 0.3 eV and a conduction band offset of 2.1 eV. The variation of the band offsets after annealing appears to be related to excess oxygen in the HfO_2. These results deviate from the electron affinity band offset model by 2.0 eV. Research supported by the ONR.

Y10.52

Radiative to non-radiative emission channels competition in thick HVPE-GaN layers grown on PENDEO templates.

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The difficulties of bulk GaN growth and the lack of lattice matched substrates for heteroepitaxy is the reason for dislocation densities of 10$_{9}$-10$_{10}$ cm^{-2} in the GaN epilayers, which limits the performance of the devices produced on such material. There has been great interest in developing buffers that, though involving more complex processing, can decrease the dislocation density further, to the range of 10$_{6}$-10$_{7}$ cm^{-2}. The technology for growth of complex buffers involves patterning or special processing prior to growth. A term of interest is the investigation of emission properties in relation to the impurity redistribution in the overgrown material. An approach to perform mask-free selective lateral epitaxial growth is the PENDEO-epitaxy. In this work, thick GaN layers are grown by hydride vapour phase epitaxy (HVPE) on templates performed by mask-free selective lateral epitaxial growth by PENDEO-epitaxy. The defect distribution relative to the different growth modes is investigated by transmission electron microscopy. The spatially resolved emission profile at different wavelengths is examined by cathodoluminescence and correlated to the different character of the growth and the distribution of the defects and impurities. Areas of enhanced as well as of reduced emission are observed and are related to enhanced radiative or non-radiative competing mechanisms. A change of the dislocation densities, their directions of propagation and type are observed. The change in the intensities of the donor bound exciton emission, donor-acceptor pair emission and free electron recombination band in the spectra taken at different areas suggests a redistribution (in type and concentration) of the impurities and native point defects, which in turn is related to the dominating growth mode in different areas.

Y10.53

The RIE Fabrication and the Ultra-high Temperature (1500°C) Annealing of the GaN Nano-rods.

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GaN-based nano structures have attracted great interest due to their potential applications to novel electronic and opto-electronic devices. The fabrication of GaN nanowires or nanorods has been achieved by using carbon nanotube-confined reaction, metal-catalyzed growth assisted by laser ablation, the high-temperature pyrolysis approach, etc. [1-6]. However, all these approaches are relatively complicated. In this paper, we report a simple fabrication of GaN nanorods by reactive ion etching and its mechanism. Furthermore, an ultra-high temperature annealing technique is developed to improve the crystalline quality of nanorods. In our approach, the MOCVD grown GaN on sapphire was deposited with ~50 nm SiO_2 film by PECVD, then dry-etched by chlorine plasma. The density of GaN nanorods obtained is 10^8-10^9/cm^2, with the diameter of ~50nm and the length of 0.5~1 μm. SEM pictures show nearly all nanorods are located in the hexagonal pits on the GaN surface. During the PEVCD process, nano-size SiO_2 crystallites (or long-range-order particles) are preferentially nucleated in the dislocation sites on the GaN surface, and more chemically inert compared to the surrounding amorphous SiO_2. Therefore they play the role as the micro-mask during the dry etching. After the rapid high-pressure thermal annealing up to 1500°C, CL measurement on GaN-nanorods shows the blue shift of band-edge (~3.4ev) emission due to the quantum-confinement effect. Besides, the bandgap modulation of GaN nano-rods was observed, CL measurement on annealed GaN nanorods demonstrates a strong emission around 3.77ev due to the intermixing between the sputtered AlN encapsulation layer and GaN nano-rods at high temperature. This dry etching method with the post-annealing at ultra-high temperature, integrated with the theoretical work of thermally induced dislocation motion, reaction, and consequently dislocation reduction in GaN we have demonstrated [7], will enable the application of GaN nanorods in nano opto-electronic devices. Reference [1] W. Han, S. Fan, Q. Li and Y. Hu: Science 277 (1997) 1287. [2] G. S. Cheng, L. D. Zhang, Y. Zhu, G. T. Fei, L. Li, C. M. Mo and Y. Q.Mao: Appl. Phys. Lett. 75 (1999) 2455. [3] C. C. Tang, S. S. Fan, M. L. de la Chapelle and P. Li: Chem. Phys. Lett. 333 (2001) 12. [4] X. Duan and C. Lieber: J. Am. Chem. Soc. 122 (2000) 188. [5] H. Peng, X. Zhou, N. Wang, Y. Zheng, L. Liao, W. Shi, C. Lee and S.Lee: Chem. Phys. Lett. 327 (2000) 263. [6] W. Q Han and A. Zettl: Appl. Phys. Lett. 80 (2002) 303. [7]H. Yu, L. McCarthy, F.Wu, S. Keller, S. Denbaars, J.Speck, U.Mishra, Oral talk, ICNS-5, Nara, Japan. May-2003

Y10.54

Non-uniform distribution of intersubband transition wavelength in MOVPE-grown AlN/GaN multiple quantum wells over a 2-inch sapphire substrate.

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Intersubband transitions (ISBTs) in quantum well (QW) structures are unique and can be applied to future optical devices, such as ultrafast all-optical switches, modulators, detectors, and quantum cascade lasers. Among many material systems, nitrides are very attractive because of their intrinsic material properties. However, the growth of such nitride-based QW structures for ISBT is difficult, particularly by metalorganic vapor phase epitaxy (MOVPE), due to the necessity for fabricating atomically flat heterointerfaces in the QW. Recently, we realized a near-infrared ISBT at a wavelength of 1.68 μm by MOVPE for the first time. To achieve the atomically flat heterointerfaces of the AlN/GaN multiple QW by MOVPE, we used GaN multi-buffer layers. Consequently, the heterointerfaces of the samples were confirmed to be comparable to or better than the molecular-beam epitaxy-grown samples. Though a short-wavelength ISBT with a small full-width at half-maximum of the transition peak was achieved by MOVPE, the role of the multi-buffer layers is still not fully understood. We therefore believe that a detailed study on a correlation between the ISBT and the structural quality is necessary for further improvement of the MOVPE-grown samples. In this study, a high-quality 150-period AlN(1.05 nm)/GaN:Si(1.65 nm) multiple QW was grown on a (0001) sapphire substrate using the same technique. An ISBT at a wavelength of 1.72 μm was observed by optical absorption measurements at the center of the 2 in. wafer. We also observed a blue-shifting of the ISBT wavelength from 1.72 to 1.52 μm as the measurement position was changed from the center to the edge of the wafer, though the structural difference of the QW was negligible. This phenomenon was investigated in terms of an inhomogeneous distribution of a built-in electric field in the QW.

Y10.55

Evidence of strong indium segregation in MOCVD InGaN

/GaN quantum layers. Pierre Ruterana[1], Greg Maciejewski[2], Greg Jurczak[2], Slawomir Kret[3] and Pawel Dluzewski[2]; [1]LERMAT, ENSICAEN, Caen, France; [2]Full Institute of Fundamental Technological Research, PAS, Warsaw, Poland; [3]Institute of Physics, PAS, Warsaw, Poland.

In this work, an investigation of a 1-5 nm diameter indium clusters in MOCVD InGaN/GaN quantum well is carried out. To this end, quantitative High Resolution Transmission Electron Microscopy (HRTEM) is coupled with image simulation with Finite Element Method (FEM) thin foil relaxation modeling. From HREM images, the measurement of the tetragonal distortion is the powerful tool for the determination of chemical composition in hetero-structures. The TEM samples used in high resolution mode were 5-15 nm thick along the 11-20 zone axis. Therefore, the foil thickness was always larger that the size of the studied nano-clusters. For a correct interpretation of the measured lattice distortion on HRTEM images one needs to take into account the strain averaging across TEM sample and inhomogeneous relaxation of the sample. We have performed 3D FEM modeling of the relaxation process as a function of a chemical composition, size and position of In cluster relative to foil surface The calculated 3D displacement fields were used to simulate the HRTEM images. The results show that the indium content can reach x=0.8 in the clusters and this much higher that was previously suggested by 2D FEM modeling

Y10.56

Fabrication of a Thermoelectric Device Using AlInN Films Prepared by Reactive Radio-Frequency Sputtering. Shigeo Yamaguchi[1,2], Ryohei Izaki[1], Yasuo Iwamura[1,2] and Atsushi Yamamoto[2]; [1]Electric, Electronic and Information, Kanagawa University, Yokohama, Japan; [2]Energy Electronics Institute, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan.

There has recently been a great increase in the research and development of thermoelectric power generation systems employing the vast resources of waste heat and environmentally sound cooling. The realization of practical applications associated with such systems requires the achievement of a high efficiency characterized by electric resistivity, thermoelectric Seebeck coefficient and thermal conductivity. At this stage, no binary compounds better than Bi_2Te_3, PbTe have been found. We have recently studied the thermoelectric properties of AlInN system in terms of the reduction in the environmentally stress. AlInN films were prepared by reactive radio-frequency (RF) sputtering. They were grown on SiO_2 glass substrates at 100 °C with a mixture of N_2 and Ar gases and they were of amorphous. The thickness of the films was about 0.3 μm. We evaluated the values of Seebeck coefficient and electric resistivity. The value of the Seebeck coefficient was negative and decreased monotonically to be -70 μV/K at 873K with increasing temperature. On the other hand, the resistivity decreased with increasing temperature, and it was about 10^{-5} Ωm. Considering both Seebeck coefficient and resistivity, we estimated the value of power factor and obtained a value of over 10^{-4}W/mK^2, which, at this stage, is smaller only by a factor of 10 compared to those for Bi_2T_3 and PbTe bulk materials. In addition, we have fabricated a thermoelectric device using nitride films, for the first time. The device structure was as follows; twenty pairs of AlInN and Au films were prepared in a serial connection by the RF sputtering on SiO_2 glass substrate. The output voltage and the output power were measured on the condition that an external load was connected with the terminals and that temperature difference of 267K was applied to the device. We obtained those two values of 0.09 V and 0.045 μW, respectively.

Y10.57

Electrical, Optical, and Magnetic Properties of Cr-doped AlN and GaN Thin Films. Stephen Y Wu[1], Hongxue Liu[1], Lin Gu[2], Rakesh K Singh[1], Louisa Budd[1], Mark van Schilfgaarde[1], Molly R McCartney[2], David J Smith[2], Nate Newman[1], Arthur J Freeman[3] and Catherine Stampfl[3]; [1]Chemical and Materials Engineering, Arizona State University, Tempe, Arizona; [2]Center for Solid State Science, Arizona State University, Tempe, Arizona; [3]Physics and Astronomy, Northwestern University, Evanston, Illinois.

We have used MBE growth to synthesize Cr-doped AlN (4-25%) and GaN (1-8%) that exhibits ferromagnetism at room temperature. Cr is found to be a deep level defect in both systems. We present experimental and theoretical evidence that ferromagnetism in these transition-metal-doped III-N systems arises as a result of a mechanism like the double exchange model, although this simple picture is not precisely correct. 7% Cr doping of AlN is found to have 33% of the defects magnetically active at room temperature. X-ray diffraction (XRD) and TEM do not find evidence of a ferromagnetic secondary phase. Small probe microanalysis and electron energy loss spectroscopy (EELS) indicates that nanoclustering of Cr_{Al} defects is present in ferromagnetic films. 2% Cr-doped GaN exhibits ferromagnetism with over 28% of the Cr magnetically active at room temperature. Electrical measurements indicate that these films follow the exponential law, $R=R_o\exp[(T_o/T)^{1/2}]$, indicating that variable range hopping between localized states in the impurity band is the dominant transport mechanism. A more complete description of the electrical, magnetic, and optical properties will be reviewed.

Y10.58

Carbon doping of Gallium Nitride using Carbon Tetra bromide in rf plasma MBE. Daniel S Green[1], Siddharth Rajan[1], Umesh K Mishra[1] and James S Speck[2]; [1]Electrical and Computer Engineering Department, University of California, Santa Barbara, California; [2]Materials Department, University of California, Santa Barbara, California.

Carbon is one the three most common impurities in GaN along with hydrogen and oxygen. Yet while oxygen is understood to be a shallow donor and hydrogen is found to occupy a deep donor level, the behavior of carbon is still poorly understood. Carbon is projected to be useful either as a shallow acceptor to produce p-type GaN or as a deep level to produce semi-insulating GaN. The carbon site is predicted to depend on the surface condition and the Fermi level during growth with the carbon generally anticipated to occupy substitutional or interstitial sites which compensate other intentional dopants and self-compensate in the case carbon is the primary dopant. To investigate the role of carbon in GaN, Carbon Tetra bromide (CBr4) was used to dope GaN grown by rf plasma MBE. CBr4 is regularly used to introduce carbon as a shallow acceptor in other III-V semiconductors and therefore is a mature technology available for MBE systems. Films were grown homoepitaxially on semi-insulating MOCVD grown templates under either Ga-rich or N-rich conditions. The growth rate was ~200 nm/hr for an rf plasma power of 150W. The CBr4 flux was studied over a range ~10^{-10} to 2x10^{-9} Torr and the substrate temperature was varied from ~600C to ~700C. Additional films were grown Ga-rich and co-doped with silicon and carbon. The samples were characterized by SIMS, AFM, Hall, and CV profiling. SIMS measurements revealed that the carbon readily incorporates under Ga-rich as well as N-rich growth conditions and yielded concentrations of ~7x10^{17} to ~2x10^{19} cm-3 for the range of incidence flux. Further, the Ga-rich growth conditions yielded sharp doping profiles (~8 nm/dec). The carbon incorporation was comparable for Ga-rich and N-rich growth, but decreased for increased substrate temperature. AFM measurements show the surface morphology is typical of undoped GaN indicating no adverse impact of the carbon doping, in contrast to etching reported when CCl4 is used as the dopant source. Hall measurements of the silicon and carbon co-doped samples with silicon doping of ~1018 were shown to have the carrier concentration reduced as the carbon concentration increased, and were resistive when the carbon doping exceeded the silicon doping. However, calculation of the compensation activity of the carbon was compromised by parallel conduction found at the regrowth interface. CV profiling verified the insulating nature of GaN:C with carrier densities less than 10^{15} cm-3, and the presence of a charge of ~10^{18} cm-3 at the regrowth interface.

Y10.59

Activation Of Beryllium Doped GaN Grown By Rf-Plasma Molecular Beam Epitaxy. Brenda VanMil, Kyoungnae Lee, Craig Swartz, Thomas H Myers, Lijun Wang and Nancy Giles; Physics, West Virginia University, Morgantown, West Virginia.

Beryllium doping has been investigated for GaN grown by rf-plasma molecular beam epitaxy on Ga-polar MOCVD grown GaN templates. All samples were grown with a growth rate of ~0.27 μm/hr. A step-doped sample with 0.5 μm Be-doped steps with 0.5 μm undoped spacers was analyzed by Secondary Ion Mass Spectrometry (SIMS). This sample exhibited symmetric steps for dopant incorporation of 10^{17}, 10^{18} and 10^{19} cm^{-3}. A series of 1 μm thick uniformly Be-doped films were grown on 0.1 μm of undoped GaN. Resistivity measurements with pressed indium contacts indicate that all uniform doped as-grown samples were semi-insulating. Samples were annealed after growth at atmospheric pressure in a tube furnace utilizing a two-stage process. The first anneal stage was in flowing forming gas (3:17 H_2:N_2) for 1 to 3 hours at temperatures ranging from 600°C to 800°C. The second stage was in flowing nitrogen at 800°C for 1 to 3 hours. All samples were inspected before and after the anneal with an Olympus BX60-M microscope with a UV florescence attachment. As-grown samples were dark blue in color. As-grown Ga-polar samples doped heavily with Be (above ~5x10^{19} cm^{-3}) exhibit orange UV florescence, and is likely associated with inversion domain formation, bringing the N-polar face to the growth surface. As-grown samples that exhibit this orange florescence have been found to be N-polar through etching experiments. The annealing process activated the orange UV florescence for the samples doped at about 10^{19} cm^{-3}, while those with lesser dopant levels remained blue. All samples remained semi-insulating after the annealing process. This work was supported at WVU by ONR Grants N00014-02-1-0974 and

N00014-01-1-0571 and was monitored by Colin E. C. Wood.

Y10.60

Mg doping of GaN with RF-Plasma molecular beam epitaxy. Czeslaw Skierbiszewski[1], Marcin Siekacz[1], Anna Feduniewicz[1], Zbyszek Wasilewski[2], Szymon Grzanka[1], Bogdan Pastuszka[1], Michal Leszczynski[1] and Sylwester Porowski[1]; [1]High Pressure Research Center, Warszawa, Poland; [2]Institute for Microstructural Sciences, National Research Council, Ottawa, Ontario, Canada.

GaN:Mg layers were grown by molecular beam epitaxy (MBE) using RF-Plasma source as a nitrogen precursor. Contrary to the GaN:Mg layers grown with ammonia, our samples does not contain hydrogen and p-type conductivity can be achieved without any post growth treatment. This makes the MBE system very attractive for effective p-type doping of GaN. We investigated growth of the Mg doped GaN layers on sapphire/MOCVD templates and on GaN bulk crystals. Secondary Ion Mass Spectroscopy (SIMS) showed that the Mg incorporation to our layers changes linearly with the Mg flux measured by Monitor Ion Gauge. Drastic improvement of the Mg doping was obtained at lower growth temperatures. For given Mg flux we were able to increase the Mg concentration measured by SIMS by 2 orders of magnitude from 1e18 cm-3 to 2e20 cm-3. On the other hand reduction of the growth temperature can lead to increase of oxygen incorporation and change of the polarity of the GaN, which in turn compensate p-type conductivity. We investigated the behavior of p-type conductivity vs. the growth temperature in details. The hole concentration at room temperature for our best samples was 5e17cm-3 and mobility 20 cm2/Vs. We will discuss the growth conditions for effective Mg doping of GaN taking into account Mg and oxygen incorporation, hole concentration and GaN layer polarity. We will demonstrate also characteristics of blue GaN/InGaN LEDs grown by RF plasma MBE on bulk substrates.

Y10.61

MBE Grown AlN Films on SiC for Piezoelectric MEMS Sensors. Dharanipal Doppalapudi[1], Richard Mlcak[1], Jeffrey Chan[1], Harry Tuller[1], Anirban Bhattacharya[2] and Theodore Moustakas[2]; [1]Boston MicroSystems Inc, Woburn, Massachusetts; [2]Electrical and Computer Engineering, Boston University, Boston, Massachusetts.

Microelectromechanical Systems (MEMS) are being extensively investigated for miniaturizing various piezoelectric sensors due to the advantages of smaller size, lower power consumption, higher sensitivity and the ability to form compact multi-sensor arrays. Such devices typically employ one or more silicon micromechanical elements (membranes, cantilever beams, tethered proof masses, etc.) and a polycrystalline piezoelectric film. The use of polycrystalline materials results in inherently less stable and irreproducible device characteristics due to difficulties in replicating the polycrystalline structure, morphology, composition, uniformity, and internal stress. In contrast, epitaxial films grown on single crystal micromechanical elements results in highly reproducible and stable devices with improved performance. AlN, in particular, has excellent piezoelectric properties for MEMS sensor applications, with an electromechanical coupling coefficient of 0.088 and a high in-plane acoustic velocity (~5700m/sec). In this paper, we present a single crystal SiC-AlN piezoelectric MEMS sensor platform fabricated by integrating MBE grown AlN films onto photoelectrochemically machined SiC micromechanical structures (microcantilevers, membranes etc). SiC and AlN have excellent lattice and thermal match enabling growth of high quality epitaxial piezoelectric films with negligible internal stress. AlN and SiC also have good acoustic match and chemical stability, providing low-loss resonators capable of long-term exposure in harsh sensor environments. Fabrication of piezoelectric AlN-SiC microresonators and flexural plate wave devices, and their application to chemical, biological and fluid sensing, is reported. Integration of III-nitride materials with MEMS creates exciting new opportunities in optical devices, sensors, actuators and RF MEMS.

Y10.62

Effect of Buffer Design on AlGaN/AlN/GaN Heterostructures by MBE. Gon Namkoong[1], W. A. Doolittle[1], A.S. Brown[2], M. Losurdo[3], M.M. Giangregorio[3] and G. Bruno[3]; [1]Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia; [2]Electrical and Computer Engineering, Duke University, Durham, North Carolina; [3]Institute of Inorganic Methodologies and of Plasmas, IMIP-CNR and INSTM, Bari, 4-70126, Italy.

A key issue for III-Nitride materials growth is the lack of high quality lattice-matched substrates. Recently, a comprehensive study of the effect of the initial growth conditions and layer design (i.e. nitridation and types of buffer layer) of the subsequent GaN epitaxial layers was reported [1]. In this work, this study is expanded to examine high temperature (700-850 øC) AlN and combined AlN/GaN buffer layer effectiveness to produce Ga-polar GaN epitaxial layers grown by radio-frequency (rf) plasma Molecular Beam Epitaxy (MBE). However, it is difficult to grow high quality AlN buffer layers due to the relatively low desorption rate and surface diffusion of Al, leading to a three-dimensional (3D) growth and Al droplets [2]. In this study, AlN growth conditions were optimized by monitoring reflection high-energy electron diffraction (RHEED). Two different growth conditions of AlN were used to avoid Al droplets. First, Al flux was increased from N rich condition to Al rich condition during growth of AlN layer to avoid Al droplets. Second, under Al rich condition, the Al shutter was toggled for every 10 sec for the first 2 minutes of growth. The etch pit density in GaN films was determined with hot phosphorous acid at 150-170 øC for 5 min. Etch pit density reduced from low $10\hat{1}0$ cm-2 for traditional AlN buffers to low $10\hat{8}$ cm-2 with Al shutter manipulation. When using a double buffer layer (low temperature GaN on high temperature AlN), etch pit density reduced to mid $10\hat{7}$ cm-2 in GaN epitaxial layers. Polarity of GaN epitaxial layers was determined by surface potential electric force microscopy and atomic hydrogen etching. Using feedback from these techniques, nitrogen inversion domains were completely removed by increasing the thickness of AlN buffer layers. Furthermore, electrical properties of AlGaN/AlN/GaN heterostructures were investigated by growing on various buffer layers. The mobility in Al0.3Ga0.7N/AlN/GaN structures grown on AlN buffer layers were ~1300 cm2/V.s at a sheet charge of $1.6x10\hat{1}3$ cm-2. Using the double buffer layer, the mobility increased to around ~1587 cm2/V.s with a sheet charge of $1.25x10\hat{1}3$ cm-2. [1] Gon Namkoong, W.A. Doolittle, A.S. Brown, M. Losurdo, P. Capezzuto, and G. Bruno, J. Cryst. Growth, 252 (2003) 159 [2] G. Ferro, H. Okumura, T. Ide, S. Yoshida, J. Cryst. Growth, 210 (2000) 429

Y10.63

Fabrication of GaN films on single crystalline ZnO deposited by molecular beam epitaxy method. Takeshi Ohgaki[1], Naoki Ohashi[1], Isao Sakaguchi[1], Takashi Sekiguchi[2] and Hajime Haneda[1]; [1]Adv. Matr. Lab., Natl. Inst. Mater. Sci., Tsukuba, Ibaraki, Japan; [2]Nanomatr. Lab., Natl. Inst. Mater. Sci., Tsukuba, Ibaraki, Japan.

Gallium nitride (GaN) and Zinc oxide (ZnO) have the same wurtzite structure and nearly the same lattice constants. Therefore, ZnO single crystals are one of the candidates for the substrate of GaN films. In this study, GaN and its related films were grown on ZnO single crystals with 0001 (Zn face), 000-1 (O face), 10-10 and 11-20 orientation using molecular beam epitaxy (MBE) method. The epitaxial relation of GaN films and ZnO substrates, the crystallinity and optical properties of the GaN films were studied. Ga metal was evaporated by Knudsen cell (K-cell) and nitrogen radicals generated by RF radical gun were irradiated during the film growth. The lattice orientation and crystallinity of the films were analyzed by X-ray diffraction and transmission electron microscopy, and the optical properties of the GaN films were investigated by photoluminescence and cathodoluminescence. The structure and optical properties of the GaN films were changed with the orientation of the ZnO substrates. The results of XRD and X-ray pole figure measurements indicate that the GaN films are grown epitaxially on the ZnO 0001 substrates. In these films, strong band-edge emission in the UV reason was observed, and the intensity of visible emission was very low. As for the films grown on ZnO with 10-10 and 11-20 orientation, the epitaxial relationship between GaN and ZnO was not simple, and the intensity of emission was very low. The structure and optical properties of the (InGa)N films grown on ZnO single crystals will be also discussed.

Y10.64

GaN layers regrown on etched GaN templates by plasma assisted molecular beam epitaxy. Lei He[1], Michael A. Reshchikov[1], Josh Spradlin[1], Jinqiao Xie[1], Faxian Xiu[1], Xing Gu[1], Feng Yun[1], Allison A. Baski[2] and Hadis Morkoc[1,2]; [1]Department of Electrical Engineering, Virginia Commonwealth Univeristy, Richmond, Virginia; [2]Department of Physics, Virginia Commonwealth Univeristy, Richmond, Virginia.

The growth of high quality GaN by plasma assisted molecular beam epitaxy (MBE) is challenging, in part due to the constraint of heteroepitaxy since GaN substrates are not yet commercially available and isotropic nature of growth. Despite the large lattice and thermal mismatch sapphire, is still the most commonly used substrate for the GaN-based devices at present. In this paper, we demonstrate a re-growth technique to obtain an improved quality GaN by MBE on a GaN on sapphire template where in the grossly defective regions have been removed. This GaN template is formed by MBE growth of GaN followed by wet chemical etching to selectively remove the defective region. Improved quality GaN was re-grown on such a template under Ga rich conditions to a thickness of about 1 micron. After re-growth, the surface of GaN is atomically smooth with spiral hillock features in the short range. The optical properties of the re-grown GaN are superior to those of MBE GaN films using sapphire as a substrate. The etch-pit density of re-grown GaN is significantly lower than that in regular MBE-grown GaN on sapphire according to the atomic-force microscopy (AFM). AFM images also reveal a 2-dimentional

re-growth initiating in regions free of extended defects. The results show that the selectively etched GaN on sapphire can be used as a good template to obtain high quality GaN.

Y10.65

Surface Control of ZrB_2 (0001) Substrate for Molecular-Beam Epitaxy of GaN. Jun Suda, Hiroyasu Yamashita, Tsunenobu Kimoto and Hiroyuki Matsunami; Department of Electronic Science & Engineering, Kyoto University, Kyoto, Japan.

Zirconium diboride (ZrB_2) has been proposed as a novel lattice-matched electrically-conductive substrate for GaN-based semiconductors [1-3]. We have demonstrated the first epitaxial growth of GaN and AlN on ZrB_2 (0001) by molecular-beam epitaxy (MBE) [2]. However, the crystalline quality of grown layer was not enough for device applications. One of reasons is thought as cleanness of ZrB_2 surface before the growth. Since this compound has a very high melting point (3220°C), high temperature (1830°C) thermal flushing is required to obtain a clean surface [4]. It is difficult to achieve such a high temperature in a standard MBE system. In fact, reflection high-energy electron diffraction (RHEED) from the ZrB_2 surface after thermal cleaning at 1000°C was faint compared to that from the GaN grown layer, indicating insufficient cleaning. In this study, we have studied ZrB_2 surfaces by X-ray photoemission spectroscopy (XPS). Besides Zr and B, O was observed. The Zr peak splits into two peaks due to a chemical shift, indicating the existence of ZrO_x in addition to ZrB_2 on the surface. After thermal cleaning at 1000°C for 30 min in an ultra-high vacuum, the peak intensity of O was decreased but still strong. Various wet chemical pre-treatments were examined. By using suitable acid pre-treatment, the peak intensity of O was much reduced and the peaks of Zr (bonded to B) and B became dominant. The combination of suitable pre-treatment and thermal cleaning resulted in sharp and intense RHEED diffraction from the ZrB_2 surface, which is a promising process for the MBE-growth of III-N on ZrB_2 substrates. [1] H. Kinoshita, S. Otani, S. Kamiyama, H. Amano, I. Akasaki, J. Suda and H. Matsunami, Jpn. J. Appl. Phys. 40 (2001) L1280. [2] J. Suda and H. Matsunami, J. Crystal Growth 237-239 (2002) 1114. [3] H. Kinoshita, S. Otani, S. Kamiyama, H. Amano, I. Akasaki, J. Suda and H. Matsunami, Jpn. J. Appl. Phys. 42 (2003) 2260. [4] T. Aizawa, W. Hayami and S. Otani, Phys. Rev. B 65 (2001) 24303.

Y10.66

The Influence of Substrate Polarity on the Blue Emission from As-doped GaN Layers Grown by Molecular Beam Epitaxy. Sergei V. Novikov[1], L. X. Zhao[1], C. T. Foxon[1], I. Harrison[2], R. P. Campion[1], C. R. Staddon[1], S. W. Kang[3], O. Kryliouk[3] and T. Anderson[3]; [1]School of Physics and Astronomy, University of Nottingham, Nottingham, United Kingdom; [2]School of Electrical and Electronic Engineering, University of Nottingham, Nottingham, United Kingdom; [3]Chemical Engineering Department, University of Florida, Gainesville, Florida.

The observation of blue luminescence in GaN layers doped with arsenic initiated active research on growth of GaN layers doped with various group V isoelectronic dopants. Blue emission has been reported for As doping of GaN layers in both metal-organic vapour phase epitaxy (MOVPE) and plasma-assisted molecular beam epitaxy (PA-MBE). Arsenic doped GaN films grown by PA-MBE on sapphire substrates show very strong blue emission at room temperature, which is more than one order of magnitude stronger than the band edge emission in undoped GaN films. Our studies show that the incorporation of As into the GaN lattice during PA-MBE is strongly influenced by the choice of substrate and its polarity. To obtain blue deep level emission from As-doped GaN requires growth under Ga-rich conditions for both sapphire substrates and (0001) GaN MOVPE templates. The exact conditions depend critically on the polarity of the GaN. To obtain strong blue emission a significantly higher Ga:N ratio is required when As-doped GaN is grown on Ga-polarity GaN (0001) templates when compared to growth of N-polarity As-doped GaN on sapphire. The influence of the polarity of the substrate on the blue emission from As-doped GaN layers grown by PA-MBE was investigated further by extending the study to non-polar directions. Arsenic doped GaN layers were grown under identical PA-MBE conditions on several types of substrates including c-plane (0001) sapphire and polar and non-polar GaN templates grown by MOVPE. Non-polar (11-20) and (1-100) GaN MOVPE templates were grown on a-plane (11-20) sapphire and LiAlO2 (100) substrates respectively. A strong influence of the substrate polarity on the optical properties of PA-MBE grown As-doped GaN layers was observed.

Y10.67

GaN Epitaxial Growth Process at High Growth Temperature by NH3 Source Molecular Beam Epitaxy. Naoki Ohshima, Akihiro Sugihara, Naohiko Okabe and Naoya Yoshida; Advanced Mat. Sci. & Eng., Yamaguchi University, Ube, Yamaguchi, Japan.

Annealing and epitaxial growth processes of GaN layer on sapphire(0001) at high growth temperatures above 900 degree C using NH3 gas source molecular beam epitaxy (MBE) have been investigated by observations of in-situ reflection high energy electron diffraction and ex-situ atomic force microscopy. It is found that the changing processes of the surface morphology and the island's shape of the GaN buffer layer deposited at a temperature of 600 degree C for 60 min strongly depend on the annealing temperature. It is noted that the surface morphology changed from islanding to columnar structure with flat surface by thermal annealing at 950 degree C. It is observed that the shape of the GaN island is changed from a particulated one to trapezoidal one with flat top surface. Furthermore, it is noted that the GaN continuous epilayer with a flat surface is appeared at a growth temperature of 1000 degree C. It is considered that the growth kinetics of GaN epitaxial layer using NH3 gas source MBE above 950 degree C is different from the one of GaN epitaxial layer at below 900 degree C. It is though that the N-terminated surface is grown above 950 degree C and the surface contained hydrogen atoms desorbed during growth at a rate proportional to the growth temperature.

Y10.68

Structural Characterization of Low-Temperature InN Buffer Layer Grown by RF-Molecular Beam Epitaxy. Tsutomu Araki[1], Tomohiro Yamaguchi[1], Masahito Kurouchi[1], Chiharu Morioka[1], Yasushi Nanishi[1] and Akira Suzuki[2]; [1]Department of Photonics, Ritsumeikan University, Kusatsu, Japan; [2]Research Organization of Science and Engineering, Ritsumeikan University, Kusatsu, Japan.

Recent developments of InN growth, especially in molecular beam epitaxy, have revealed the excellent electrical properties and new findings in the band-gap energy, which open new application fields of InN-based nitride semiconductors such as high-speed electronic devices, long wavelength optical devices and solar cells. Usually InN films are grown on substrates using a buffer layer. So far, low-temperature (LT) InN [1], LT-InN/LT-GaN [2] and high-temperature AlN [3] layers were used as the buffer layer and are found to be essential to obtain high quality InN films. However, InN films still have high density threading dislocations, large twist distribution and voids at interface between the film and the substrate. Therefore, the roles of the buffer layer in the InN growth should be understood for further improvements of the quality of InN films. In this paper, we will report on micro-structure of LT-InN buffer layers characterized by TEM. InN growth was performed by RF-MBE on (0001) sapphire. After nitridation of the substrates, a LT-InN buffer layer was grown at 300°C for 10 min (about 30nm), which followed by the InN growth at 530°C. The samples were observed with JEOL 2010 and HITACHI H-9000UHR electron microscopes operated at 200 kV and 300 kV, respectively. In the LT-InN buffer layer, defective regions were observed, which might be due to low temperature growth at 300°C. Three dimensional islands were also observed, in which growth orientation was disordered. These islands are found to be one of the origin of threading dislocations. [1] Y. Saito et al., Jpn. J. Appl. Phy. 40, L91 (2001), [2] M. Higashiwaki et al., Jpn. J. Appl. Phy. 42, L540 (2002), [3] H. Lu et al., Appl. Phys. Lett. 79, 1489 (2001).

Y10.69

Surface Termination Control of GaN Growth Using MOMBE. Isaiah Steinke[1,2], Bentao Cui[1,2] and Philip I Cohen[2,1]; [1]Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, Minnesota; [2]Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, Minnesota.

The growth and kinetics of GaN have been studied using metal organic molecular beam epitaxy (MOMBE) using triethylgallium (TEG) and ammonia (NH_3). Though different reconstructions are not observed, the adsorption of one and two layers of Ga are found to be observed in the decrease of the specular beam intensity when the ammonia flux is removed. A procedure is developed to allow growth under excess N conditions or under one or two layers of Ga. The surprise is that under excess N conditions, smooth, step-flow growth is obtained even though substrate temperatures are near 750°C, typical of that used in Ga effusion cell MBE growth of GaN. Under MBE, similar conditions would correspond to diffusion limited, rough growth. Starting from MOCVD GaN templates, the growth and morphology under the different terminations was compared. Under excess N conditions, ammonia pressures were 5×10^{-5} torr and the TEG pressure was 1×10^{-5} torr. Based on the observed crossover and known ammonia dissociation, we estimate that at these conditions, the TEG dissociation rate is about 10%. Under excess N conditions on a low-index substrate, hillock growth was observed with terrace lengths of about 40 nm. The ammonia flux was then decreased, keeping the TEG flux constant, changing to a termination of one layer of Ga. Under these conditions the hillock terrace length increased to about 100 nm, even though the growth rate was roughly the same, 0.6 ML/s. This suggests a change in the step-edge energy. On these surfaces no step bunching was observed, in contrast to previous

MOCVD work at similar growth temperatures.

Y10.70

Polarity inversion and in-plane periodic polarity structures based on GaN. Sebastien Pezzagna, Nicolas Grandjean and Philippe Vennegues; CNRS-CRHEA, Valbonne, France.

It is observed during the growth by NH3-molecular beam epitaxy of GaN that a polarity inversion from Ga to N occurs when a large Mg flux is used. The interface between the two polarities is perfectly flat over a 2 inch wafer and no dislocation is introduced by the polarity change. Actually, the quality of the N-polarity GaN growing layer replicates that of the Ga-polarity underlayer. Transmission electron microscopy (TEM) images reveal a faceted interface. Secondary ion mass spectroscopy shows that the critical Mg concentration for a polarity inversion must be larger than 3x1020 cm-3. Despite some indications about the role of the Mg, the actual mechanism responsible for the polarity inversion is still unclear. Furthermore, if the growth proceeds on the N-polarity and with a large Mg flux, the GaN layer undergoes a crystal phase transition from hexagonal to cubic; the interface between h- and c- GaN being perfectly flat at the atomic scale. On a sample with a single Ga/N polarity inversion along the growth axis, stripes have been etched up to the Ga polarity by reactive ion etching. At this stage the sample exhibits an in-plane Ga/N periodic polarity modulation. GaN is then overgrown in order to achieve thick periodic polarity structures. The vertical polarity domain boundary is investigated by TEM as a function of stripe orientations. Selective wet etching using KOH reveals smooth (10-10) planes for properly chosen stripe orientation.

Y10.71

Characterization of Photovoltaic Cells Using n-InN/p-Si Grown by RF-MBE. Chiharu Morioka[1], Tomohiro Yamaguchi[1], Tsutomu Araki[1], Yasushi Nanishi[1], Akira Suzuki[2] and Hiroyuki Naoi[3]; [1]Dept. of Photonics, Ritsumeikan Univ., Kusatsu, Shiga, Japan; [2]Res. Org. of Sci. & Eng., Ritsumeikan Univ., Kusatsu, Shiga, Japan; [3]Center for Promotion of The 21st Century COE Program, Ritsumeikan Univ., Kusatsu, Shiga, Japan.

A newly established narrow band gap for indium nitride (InN) means that the indium gallium nitride system of alloys (InxGa1-xN) covers the almost full solar spectrum. Therefore, InxGa1-xN is a very attractive material for high-efficiency solar cells. In this paper, we characterized, for the first time, photovoltaic cells using n-InN/p-Si heterojunction grown by radio frequency molecular beam epitaxy (RF-MBE). The n-InN/p-Si heterojunction was formed by epitaxial n-InN films grown on p-Si(111) and p-Si(100) substrates using RF-MBE. The substrates were of p-type conductivity with a resistivity of 0.02-10 Ωcm. Thickness of Si substrates was 370-530 mm. Growth rate of InN films was approximately 250 nm/h. The surface morphology of InN films was smooth and flat. The material employed for ohmic contacts was Aluminum, which was deposited by conventional vacuum evaporation. On the surface of InN films, circular electrodes with a diameter of 1 mm were formed; the back side of Si substrate was entirely covered by the electrode. The size of the sample was 0.5 cm x 0.5 cm. Dark I-V characteristics and I-V characteristics in an air mass 1.5 global (AM 1.5G) condition using a solar-simulator were measured at room temperature. The dark I-V characteristics showed clear rectifying characteristics. The I-V characteristics in an AM 1.5G condition showed a photovoltaic effect. The short-circuit current was Jsc=3.95 mA/cm2 and the open-circuit voltage was Voc=0.083 V. Further studies should be necessary for the improvement of the photovoltaic properties, but these results clearly demonstrate for the first time the potential for realization of solar cells using InN-based materials.

Y10.72

Low-Temperature Epitaxial Growth of Ultrasmooth AlN Films on Sapphire Substrates by Laser MBE. Jin Liu[1], Atsushi Sasaki[1], Shuhei Sato[1], Norihiro Tateda[1], Mamoru Yoshimoto[1], Masaru Yamada[2], Tokuo Yodo[2] and Keisuke Saito[3,1]; [1]Materials and Structures Laboratory, Tokyo Institute of Technology, Yokohama, Kanagawa, Japan; [2]Osaka Institute of Technology, Osaka, Japan; [3]Spectris Co. PANalytical, Tokyo, Japan.

So far, we have reported the room-temperature epitaxial growth of several oxide films by laser MBE, i.e. pulsed laser deposition in ultrahigh vacuum. Laser MBE technique supplying highly-excited film precursors was verified to be useful for low-temperature epitaxial growth of films. On the other hand, we have examined the polarity of wurtzite GaN films using in-situ coaxial impact collision ion scattering spectroscopy (CAICISS), in order to elucidate the atomic-scale growth behavior of nitride films. In this paper, we report on the low-temperature (close to room-temperature) epitaxial growth of ultrasmooth AlN films by laser MBE method using AlN target as well as on the polarity characterization. AlN thin films were deposited on sapphire (0001) substrate without or with buffer layers by laser MBE with KrF excimer laser (wavelength; 248 nm, 20 ns duration, 5 Hz). The films were characterized by RHEED, CAICISS, XRD, AFM, and SEM. In the case of using a buffer layer of NiO ultrathin film (10 nm thick) we could grow the epitaxial AlN film at room-temperature. The RHEED pattern of as-deposited AlN film was streaky, and XRD analysis indicated that AlN films grew epitaxilly with (0001) orientation. Surface morphology of the AlN epitaxial films grown at room-temperature showed the atomic step structure with ultrasmooth terraces. We also present the effects of buffer layers and substrate nitridation on the growth direction, +C or -C of AlN epitaxial films.

Y10.73

Growth of (Ga,Mn)N a Diluted Magnetic Semiconductor by Chemical Beam Epitaxy (CBE). Angela Carreno[1], Chris Boney[2], Alexander Litvinchuk[3] and Abdelhak Bensaoula[2]; [1]Chemistry -TcSAM, Univ. of Houston, Houston, Texas; [2]Physics - TcSAM, Univ. of Houston, Houston, Texas; [3]Raman Spectroscopy-TcSAM, Univ. of Houston, Houston, Texas.

The GaN material system is a very promising candidate for the realization of electronic devices based on diluted magnetic semiconductor (DMS) films. The incentive behind studying DMS materials is their potential to form high-density magnetic memory integrated IC's, semiconductor based magnetic sensors, magneto optical devices for communication systems, and other spin-based and photonic-based applications. Many reports have indicated that high doping levels of Mn in GaN lead to ferromagnetic materials with Curie temperatures at or above room temperature. To date (Ga,Mn)N has been fabricated by several epitaxial and non-epitaxial techniques. However to our knowledge, we are the first to report the epitaxial growth of (Ga,Mn)N by CBE. (Ga,Mn)N has been grown on sapphire substrates using TEG, NH_3, and solid Mn as precursors. Bright 2D RHEED images exhibiting the six-fold streaky (1x1) patterns have been obtained, suggesting retention of the wurtzite structure. Very smooth (Ga,Mn)N films have been grown with Mn concentrations between 0.5-2.0% as determined by EMPA and XPS. XPS depth profiling verifies that the Mn is of uniform concentration throughout the films and XRD scans have not detected the presence of secondary phases besides the wurtzitic structure. In addition to RHEED, the CBE chamber employs two Time of Flight Ion Scattering Spectroscopy techniques, Direct Recoiled Spectroscopy (DRS) and Mass Spectroscopy of Recoiled Ions (MSRI). MSRI has been used as an in-situ, real time technique, which allows the surface composition information of film components and impurities to be determined during the growth process. MSRI has been used to: 1)monitor the efficiency of the degassing process in removing carbon impurities from sapphire; 2)assure preparation of a completely nitridated sapphire substrate surface; 3)prepare a continuous, high quality GaN buffer layer on the nitridated sapphire substrate; and 4)detect the incorporation of Mn into the GaN matrix in order to correlate Mn incorporation rates with growth parameters. DRS is also capable of determining structural characteristics of the outermost atomic layers of the surface. Scattering-recoiling scans at a grazing angle determined that all samples are metal polar. This was confirmed by chemical etching. The GaN surface periodicity determined by plotting the relative intensity as a function of the azimuthal rotation was consistent to published data by Ahn et al. Data from (Ga,Mn)N surfaces are being analyzed to establish any distortion of the crystalline structure due to Mn inclusion. Room temperature Raman spectra showed characteristic GaN signals in addition to two unreported previously peaks appearing in all (Ga,Mn)N samples at 695.3 and 763.8 cm^{-1}. Detailed analysis of these signals and their possible correlation with Mn concentration is being established. Magnetic properties characterization of the (Ga,Mn)N films is currently underway and will be reported.

Y10.74

Properties of Crucible Materials for Bulk Growth of AlN. Glen Slack[1,2], Jon Whitlock[1], Kenneth Edward Morgan[1] and Leo Schowalter[1,2]; [1]Crystal IS, Inc., Crystal IS, Inc., Watervliet, New York; [2]Physics, RPI, Troy, New York.

A variety of different crucible materials have been suggested and/or employed for the sublimation-condensation growth of AlN single crystals above 2000 C. Representative materials all have melting points well above 2300 C, a reasonable degree of chemical compatibility with AlN, relatively low vapor pressures, and relatively small thermal expansion coefficients. We analyze the current state of knowledge on crucible materials such as C, W, Re, W-Re alloys, BN, HfN, HfC, NbC, TaC, Ta2C, TaN, ZrC and ZrN with respect to published bulk AlN growth conditions. Crucible materials pyrolytic graphite, pyrolytic BN, and W have integrated thermal contraction values (upon cooling from growth temperatures) that are less than that of AlN; the other materials have larger values. The lowest vapor pressure materials in a nitrogen atmosphere are W, TaC, and Re; thus they are expected or have been shown to yield higher purity crystals than the other candidates. The materials C, BN, Hf, and ZrN yield

higher impurity levels in the AlN crystals.

Y10.75
Synthesis, Structure and Luminescence of High Brightness Gallium Nitride Powder. Rafael Garcia, Abigail Bell, Michael Stevens and Fernando A Ponce; Physics & Astronomy, Arizona State University, Tempe, Arizona.

Highly luminescent GaN powders have been synthesized by reacting high purity gallium metal with ultra-high purity ammonia. The resulting GaN powders are thousands of times more cathode- and photo-luminescent than other GaN powders including commercially available material. Their luminescence intensities are comparable to that of GaN grown by hydride vapor phase epitaxy. GaN powders have many possible applications including electroluminescent lamps in appliances such as cell phones and car dash boards. GaN powders can also be used as precursors for growth of GaN thin films by pulsed laser deposition. Some improvements have been made on the synthesis route developed by Johnson *etal*[1]. Our improved method produces hexagonal GaN powders with high luminescence efficiency without the need for post-growth treatment. The material has been obtained by a complete reaction between high purity gallium metal (99.999%) and ultra-high purity ammonia (99.9995%) in a horizontal quartz tube reactor at 1000 °C. The powders produced in this reactor consist of light grey micro-crystals with wurtzite structure. Elemental analysis indicate that the powders obtained by this method have a high nitrogen concentration (more than stoichiometric GaN, 16.73%). Powder X-ray diffraction demonstrates that the material has a high purity and single crystalline structure. Electron microscopy shows that the powders consist of at least two kinds of particles, small sized platelets and large sized needles. The GaN powders obtained by this method produce high efficiency ultra-violet luminescence around 370 nm (3.35 eV, near band-edge emission) when they are excited by accelerated electrons (cathodoluminescence) or by high energy photons (photoluminescence) at room temperature. [1] W.C. Johnson, J.B. Parsons, and M.C. Crew, J. Phys. Chem., **36**, 2651 (1932).

Y10.76
Ultra-Thin Silicon Nitride Layers for GaN Epitaxy on Si(111). Thomas Schmidt[1], Torben Clausen[1], Subhashis Gangopadhyay[1], Jens Falta[1], Luca Gregoratti[2], Maya Kiskinova[2] and Stefan Heun[2]; [1]Institute of Solid State Physics, University of Bremen, Bremen, Germany; [2]Sincrotrone Trieste, Basovizza, Italy.

Silicon nitride layers with a thickness of $\leq$2 nm grown on Si(111) have been characterized with respect to their chemical and structural properties employing microscopy, spectroscopy, and diffraction techniques. The films were grown by reactive N deposition from rf and ECR plasma sources at substrate temperatures ranging from 700° C to 1050° C. From scanning tunneling microscopy (STM) measurements at submonolayer coverages, the formation of a well ordered interface is observed. The persistence of the surface reconstruction up to the saturation thickness, as observed by low energy electron diffraction, reveils a crystalline growth. Integral and spatially resolved x-ray photoemission spectroscopy measurements are in agreement with a homogenous Si_3N_4 stoichiometry. The spectromicroscopy results imply an increased roughness of the nitride layers at high deposition temperatures. This is confirmed by the investigation of the film morphology by in-situ STM and ex-situ AFM. At lower temperatures, the films are homogenous and almost atomically smooth. In addition, such Si_3N_4 layers have been used as buffer layers for subsequent growth of GaN films. First STM and x-ray scattering results are presented.

SESSION Y11: Processing
Chair: Suzanne Mohney
Friday Morning, December 5, 2003
Room 312 (Hynes)

8:30 AM Y11.1
Gate leakage suppression and contact engineering in nitride heterostructures. Yuh-Renn Wu[1], Madhusudan Singh[1], Jasprit Singh[1] and Umesh K Mishra[2]; [1]Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan; [2]Electrical and Computer Engineering, University of California, Santa Barbara, California.

In conventional semiconductor junctions between metals and semiconductors, the properties of the junction can only be altered by doping once a metal and semiconductor are chosen. In polar semiconductors where fixed interface charge can be produced, the junction's properties can be tailored to range from Ohmic to tunneling to blocking by small changes in design. In this work, we will present results of a self consistent model of current-voltage characteristics in a metal-polar semiconductor junctions. It is known that due to a very strong piezoelectric effect and large spontaneous polarization in nitrides, fixed charge densities as high as 5×10^{13} cm^{-2} can exist at the interface, as a result of its polar nature. An even stronger degree of polarization exists in ferroelectric materials. These charges can cause very large band bending and possibly induce a two dimensional electron or hole gas. To study nitride and ferroelectric junctions and consider the effect of adding high-κ layers, we have developed a new model, the drift-diffusion-charge-control model, which is an improvement on our earlier charge control model. It addresses charge control as well as transport through tunneling and drift-diffusion. This model is applied to examine properties of three classes of junctions that are important in devices: i) metal/AlGaN/GaN structures that are used in nitride heterojunction field effect transistors; ii) metal/high-κ insulator/GaN/AlGaN structures for potential applications in very small gate devices to suppress gate tunneling current; iii) metal/polar insulator/GaN/AlGaN junction with practical application for low source resistance regions. The physical parameters used for high-κ dielectrics and polarization charges reflect values typically found in ferroelectric materials. Some of the key results of our studies are: i) extremely low resistance, undoped Ohmic contacts can be formed on large band gap semiconductors if $\sim 20\AA$ of a high quality polar material with a polarization value of 10^{14}cm^{-2} can be incorporated. We find that the tunneling current density is increased by a factor of nearly 10^5 (in either bias condition) when compared to the structure without any polar layer. Using such undoped contact techniques would have a major effect on large band gap semiconductor contact technology; ii) Highly non-linear junctions with tailorable turn-on voltages can be designed by choosing a barrier layer thickness within a certain range. Below this range, the junction becomes blocking; iii) Up to four orders of magnitude of current suppression can occur with the use of a thin high-κ ($\sim$30) region. This reduction can occur with essentially no change in the capacitance-voltage characteristics of the junction.

8:45 AM Y11.2
Formation of thin GaN microdisks supported by InGaN pedestals using photoelectrochemical etching.
Elaine D Haberer[1], Andreas Stonas[2], Rajat Sharma[1], Shuji Nakamura[1], Steve DenBaars[1] and Evelyn L Hu[2]; [1]Materials Dept., UCSB, Santa Barbara, California; [2]Electrical and Computer Engineering Dept., UCSB, Santa Barbara, California.

Microdisks have been used in GaAs and InP materials to form extremely high quality resonators for optical devices, ultimately resulting in low-threshold lasing. A microdisk is a thin semiconductor disk surrounded by a lower index material. Through total internal reflection, the circular geometry of the disk gives rise to low loss whispering gallery modes (WGMs) which propagate along the periphery of the disk. The GaN material system is well-suited for the microdisk structure because other mirror geometries such as cleaved mirrors and several period epitaxial mirrors can be problematic. The difficulty in forming a GaN microdisk is the ability to optically isolate the disk. In other material systems optical isolation of the WGMs is generally achieved by using a selective wet etch to lift-off or undercut the disk, forming a pedestal. Because GaN-based materials do not have a simple wet etch, we must use another method to optically isolate the disk. We have chosen to use InGaN/GaN bandgap selective photoelectrochemical etching (PECE). In this technique, the sample is immersed in an electrolyte solution and exposed to filtered light from a Xe lamp. The filter allows photons with energy less than the bandgap of GaN to pass, generating electrons and holes in the InGaN. The holes drift to the InGaN/electrolyte interface where they drive the photo-induced etch. In previous studies, we have used a single composition, 100 nm $In_{0.12}Ga_{0.88}N$ sacrificial layer with KOH as the electrolyte to lift-off 1 micron thick GaN microdisks. Because of finite selectivity and non-optimized etch conditions, the undercut surface was so rough it was necessary to use chemical-mechanical polish to smooth the disk following lift-off. In the latest research we have explored several different PECE conditions and have designed different epitaxial structures for the sacrificial layer. We have found that we can significantly reduce the roughness of the undercut by (1) increasing the InGaN/GaN selectivity using HCl as the electrolyte and (2) more uniformly confining the holes using an $In_{0.04}Ga_{0.96}N/In_{0.09}Ga_{0.91}N$ superlattice. We have fabricated 120 nm thick GaN microdisks which do not require lift-off and polishing, but actually sit upon 220 nm InGaN pedestals. This study explores the optical emission of the GaN microdisks.

9:00 AM Y11.3
Vanadium-Based Ohmic Contacts to High Al Fraction AlGaN.
Jimmy H. Wang[1], Sammy H. Wang[1], Russell D. Dupuis[2], Uttiya Chowdhury[2] and Suzanne E. Mohney[1]; [1]Department of Materials Science and Engineering, The Pennsylvania State University, University Park, Pennsylvania; [2]University of Texas, Austin, Texas.

As group III nitride emitters are developed for operation at shorter wavelengths, there is a need for ohmic contacts to n-type AlGaN with

higher Al fractions. For n-$Al_{0.44}Ga_{0.56}N$ and n-$Al_{0.6}Ga_{0.4}N$, we previously compared Ti/Al/Pt/Au ohmic contacts (similar to those used for n-GaN and nitride HEMTs) to a new V/Al/Pt/Au contact. In both cases, the optimized contact with V as the first layer provided a lower specific contact resistance and required lower annealing temperatures than did the optimized contact with Ti as the first layer. On n-$Al_{0.6}Ga_{0.4}N$, a specific contact resistance of 4×10^{-5} Ohm cm^2 was achieved. In this presentation, we describe TEM and AFM characterization of the V/Al/Pt/Au contact as well as successful efforts to reduce the specific contact resistance and improve upon the surface morphology of our contacts. Through TEM, we learned that the interface between the annealed V/Al/Pt/Au contact and $Al_{0.6}Ga_{0.4}N$ is planar and that consumption of the semiconductor by the metallization is minimal. However, the surface of the contact is not very smooth, with an RMS roughness of 110 nm measured by AFM. By replacing the Pt layer with Pd and optimizing the layer thicknesses, we were able to reproducibly reduce the specific contact resistance by an order of magnitude, providing an average specific contact resistance of 3×10^{-6} Ohm cm^2. Initial experiments indicate that replacing the Pt with V also allows us to reduce the specific contact resistance and improve upon the surface morphology of the contacts. Further characterization of the contacts by TEM is underway to provide a comparison between the metal/semiconductor interfaces of the contacts in an effort to understand why some of the metallization schemes provide a lower contact resistance than others.

9:15 AM Y11.4
Reduction of the p-type contact resistance in GaN-based laser diodes. Andreas Weimar, Alfred Lell, Andreas Leber, Stephan Miller, Volker Kuemmler, Georg Bruederl and Volker Haerle; OS T2, OSRAM Opto Semiconductors, Regensburg, Germany.

For GaN-based laser diodes there will be various applications in near future like optical data storage, laser printing and projection displays. At OSRAM Opto Semiconductors, blue laser diodes are developed since 1998, which led to the first continuous wave operation in Europe in 2001. The (Al,Ga,In)N-compound semiconductor layers are grown by MOVPE on 2-inch SiC-substrates. The comparison of published laser diode lifetimes of various groups leads to the conclusion that the most limiting factors for the laser diode lifetime are the high dislocation density as well as the heat generation by electrical losses. In the latter case, the p-type contact resistance plays an important role because of its large contribution to the operation voltage. In this work, we present results of systematic investigations concerning the impact of technological parameters on the specific contact resistance including the choice of the contact metal with regard to its work function, the p-GaN surface preparation, hydrogen incorporation by a typical PECVD-process as well as the dependence of the contact resistance on the Mg-doping concentration. The results of these investigations were implemented in the p-type contact technology of laser diodes. By those changes, the operation voltage of the laser diodes was lowered from 33 V to 6 V. The reduction of the operation voltage and thus the operation power was an essential contribution to the increase of the laser diode lifetime to the current best value of 143 h.

9:30 AM Y11.5
Influence of metal thickness to sensitivity of Pt/GaN Schottky diodes for Gas sensing applications. Vinayak Tilak[1], Majdeddin Ali[2], Volker Cimalla[2], Peter Sandvik[1], Jeff Fedison[1], Oliver Ambacher[2] and Danielle Merfeld[1]; [1]GE, Global Research, Niskayuna, New York; [2]Center of Micro- and Nanotechnologies, Technical University Ilmenau, Ilmenau, Thuringia, Germany.

A hydrogen gas sensor based on a Pt/GaN Schottky diode structure was fabricated and the behavior of the device to hydrogen was studied. Pt/GaN Schottky diodes were fabricated on Si doped GaN layer (ND = 9×10^{16}) grown with a thickness of 3 μm on sapphire substrates. Ohmic contacts were processed by evaporating Ti/Al metal stacks and annealing at 800C for 1 minute in nitrogen atmosphere. Three different sets of Schottky diodes were fabricated each with 80 $\AA$, 240 $\AA$ and 400 $\AA$ of Platinum as top contacts evaporated using e-beam evaporation. All three sets of devices were passivated using silicon dioxide. Gold bond pads were evaporated on the Ohmic and Schottky electrodes. The devices were then wire bonded to a 16 pin package. An external heating element was present in the package to which the device was mounted on in order to increase the temperature of the device up to 365C. The electronic performance of a 0.25 x 0.25 mm^2 Schottky diode was tested in 1 % by volume, hydrogen gas diluted by nitrogen for gas sensor applications. The devices were operated in constant current mode (5 mA constant current) in a forward bias condition. The temperature was controlled by applying a constant voltage to the external heater and measuring the temperature using a thermocouple. The change in voltage of the diode at a fixed current was monitored with the diode exposed to hydrogen and for comparison to dry air at different temperatures. The response, as measured by the change in voltage increased as the thickness of the Schottky metal contact decreased at any given temperature. For example at 365C, the exposure of the Pt/GaN diode by hydrogen for the 80 $\AA$, 240 $\AA$ and 400 $\AA$ Schottky metal contacts caused a response of 328 mV, 246 mV and 193 mV, respectively. Furthermore, the sensitivity increased with increasing temperature for all Pt thickness starting from room temperature to 310C, beyond which the sensitivity decreased for the 240 $\AA$ and 400 $\AA$ Schottky contact devices. The sensitivity of the 80 $\AA$ Schottky contact devices continues to increase up to 365C, the temperature to which these measurements were performed. The trend of increasing response with decreasing thickness was also observed in 0.5 x 0.5 mm^2 and 1.0 x 1.0 mm^2 size Schottky diodes. The increase in sensitivity to decrease in thickness points to the dissociation of molecular hydrogen on the surface, the diffusion of atomic hydrogen through the bulk platinum and the adsorption of hydrogen to the surface as a possible mechanism of sensing of hydrogen by Schottky diodes [1]. Very likely, the thinner metal facilitates the easier diffusion of atomic hydrogen through the bulk platinum causing a higher sensitivity. Reference: [1] J. Schalwig, G. Müller, U. Karrer, M. Eickhoff, O. Ambacher, M. Stutzmann, L. Görgens, G. Dollinger, Appl. Phys. Lett. 80, 1222 (2002).

9:45 AM Y11.6
Low resistance ohmic contacts to AlGaN/GaN heterostructure field effect transistors. Deepak Selvanathan, Asrat Tesfayesus, Vipan Kumar and Ilesanmi Adesida; Electrical and Computer Engineering, University of Illinois, Urbana, Illinois.

Wide bandgap GaN-based heterostructure semiconductors are of interest in the area of high frequency, high temperature and high power electronic device applications. High quality ohmic contacts with low contact resistance (< 0.5 Ω-mm) are essential to fabricate such high performance devices. Ti/Al/Ti/Au, Ti/Al/Ni/Au and Ti/Al/Pt/Au metallization schemes are the standard approach to achieve low resistance ohmic contacts to AlGaN/GaN heterostructure field effect transistors (HFETs). Previously, we had proposed the use of Ti/Al/Mo/Au ohmic metallization scheme for formation of ohmic contacts on AlGaN/GaN HFETs. These contacts exhibit low contact resistance of 0.20 Ω-mm and are thermally stable for 25 h at 600 øC. In this work, we compare the ohmic characteristics of Ti/Al/Mo/Au, V/Al/Mo/Au and Mo/Al/Mo/Au metallization schemes on AlGaN/GaN HFETs. The ohmic performance of the contacts is characterized based on transfer length measurements (TLM) and current-voltage (I-V) measurements. The variation of contact resistance and specific contact resistivity of the ohmic contacts has been studied as functions of the anneal temperature for the three metallization schemes. From the TLM measurements, Ti/Al/Mo/Au ohmic contacts exhibit low contact resistance with a value of about 0.25 Ω-mm when annealed at 850 øC. V/Al/Mo/Au ohmic contacts exhibit high surface roughness and poor edge acuity when annealed at high temperatures with a contact resistance of 0.35 Ω-mm and Mo/Al/Mo/Au ohmic contacts are more stable with a contact resistance of 0.27 Ω-mm. Results on our investigation of the long-term thermal stability of these contacts at higher temperatures will be presented. The surface morphologies of the three types of ohmic contacts are characterized using atomic force microscopy measurements. The intermetallic reactions occurring during ohmic contact formation are studied using Auger electron spectroscopy (AES). Ohmic contact formation mechanisms for AlGaN/GaN HFETs will be discussed.

10:30 AM *Y11.7
Ohmic contact to n-type and p-type (Al)GaN semiconductors. Ilesanmi Adesida, Deepak Selvanathan and Hyun-Kyong Cho; Department of Electrical and Computer Engineering, University of Illinois Urbana-Champaign, Urbana, Illinois.

The direct bandgap of GaN-based semiconductors have made them attractive materials for the realization of a wide range of optoelectronic devices. Examples of devices that are either commercially available or have been demonstrated include short wavelength light emitting diodes (LEDs), solar blind detectors, and laser diodes which have applications in white light illumination, bio-chemical agent sensing, solar UV detection, missile detection, flame and heat sensing, ozone monitoring, and remote sensing. Materials growth and device processing are still critical issues in terms of obtaining highly efficient GaN-based optoelectronic devices. The realization of highly reliable, thermally stable, low resistance ohmic contacts to both n-type and p-type GaN-based semiconductors is essential. To date, the formation of contacts to AlGaN with high Al concentration remain a challenge for various reasons. In this paper, we will describe our work on ohmic contact formation on both n-type and p-type AlGaN of various Al concentrations. Results on n-type contact formation using Ti/Al/Mo/Au and other metallization schemes will be presented. Contact formation to p-type AlGaN using Pd-based metallization schemes will be presented. Issues of thermal stability of these contacts will be discussed. The efficacy of various surface treatment schemes for GaN and AlGaN to improve the ohmic

performance of the contacts will be discussed. Comprehensive studies are being performed to compare the effects of various surface treatment schemes, which include both plasma and wet processes on the electrical and material characteristics of GaN and AlGaN semiconductors. Further, the mechanism of formation of ohmic contacts in these semiconductors will be discussed. This work was supported by DARPA and ONR Grants.

11:00 AM Y11.8
GaN Microstructures Formed by Polarity-Selective Chemical Etching. Aref Chowdhury, Hock M. Ng, Wolfgang Parz and Nils G. Weimann; Bell Laboratories, Murray Hill, New Jersey.

The ability to fabricate microstructures such as photonic crystals is of importance because these structures enable us to control and manipulate the behavior of light. As such, it is desirable to fabricate GaN microstructures because of the material's wide window of transparency from 365 nm - 13.6 μm. However, the strength of the Ga-N bond (8.92 eV/atom) results in the material being chemically very stable. Thus, the focus of research for attaining reasonable etch rates has been on dry etching techniques such as reactive ion etching, inductively coupled plasma etching and chemically-assisted ion beam etching. However, mask erosion during the dry etching process results in slanted sidewalls for etch depths greater than 1 micron. In this work, we present 1-D and 2-D GaN microstructures fabricated by polarity-selective chemical etching. This fabrication technique involves growing a pattern of Ga- and N-polar regions by plasma-assisted molecular beam epitaxy and then subjecting the sample to a KOH solution. The process does not require an etch mask as the KOH selectively etches the N-polar regions, thus forming the GaN microstructure. Etch depths of up to 4 microns have been achieved with very smooth vertical sidewalls. The particular GaN microstructures that will be presented are a 1-D grating and a 2-D lattice of hexagonal holes.

11:15 AM Y11.9
Device and Process Optimization of AlGaN/GaN Current Aperture Vertical Electron Transistors (CAVET) fabricated by Photoelectrochemical wet etching. Yan Gao[1], Ilan Ben-Yaacov[2], Umesh Mishra[2], Steven DenBaars[1,2] and Evelyn Hu[1,2]; [1]Materials Department, University of California, Santa Barbara, Santa Barbara, California; [2]Electrical and Computer Engineering Department, University of California, Santa Barbara, Santa Barbara, California.

We have previously reported that fabrication of AlGaN/GaN Current Aperture Vertical Electron Transistors (CAVETs) formed by photoelectrochemical (PEC) wet etching. The current aperture in our CAVETs was formed through the bandgap-selective etching of a thin (60 nm), InGaN sacrificial layer incorporated into the device structure. The initial device results showed a large voltage offset around 2-3V, and current density around 0.3A/mm [1]. The offset was related to the large electron barrier arising from the built-in piezoelectric field in the unintentionally doped, strained InGaN layer. Doping the InGaN layer n-type should screen the piezoelectric field, and reduce the electron barrier, however this change in the material composition dramatically degraded the smoothness and selectivity of the KOH-based PEC etch process we had developed. A parallel effort in device structure design and PEC process development resulted in a new CAVET device having significantly reduced offset (0.7V), with Imax = 0.32A/mm, and gm=67mS/mm.The material structure was modified to remove the barrier to electron flow and to ensure sufficient hole confinement to enable efficient and selective PEC etching. The process optimization incorporated a variety of etchants (KOH, HCl, H2SO4/H2O2) and etching conditions. We will discuss both the device and process optimization, as well as the RF performance of this CAVET. [1] Y. Gao, A. R. Stonas, I. Ben-Yaacov, U. K. Mishra, S. P. DenBaars, E. L. Hu, AlGaN/GaN Current Aperture Vertical Electron Transistors (CAVET) fabricated by Photoelectrochemical wet etching, published in Electronics Letters, vol 39(1), 148-149 (2003)

11:30 AM Y11.10
Laserdiode Facette Degradation Study.
Ulrich Theodor Schwarz[1], Thomas Schoedl[1], Volker Kuemmler[2], Alfred Lell[2] and Volker Haerle[2]; [1]NWF II - Physik, Regensburg University, Regensburg, Germany; [2]Osram Opto Semiconductors GmbH, Regensburg, Germany.

We study the aging behaviour of GaN gain guided laser diodes on SiC substrates with cleaved facets and reflective coatings on none, one, or both facets. This allows us to demonstrate that in addition to volume effects there is a contribution of the laser facets to laser degradation. We observe that for the uncoated laser diodes the threshold current density is increasing considerably faster compared to laser diodes with mirror coatings. Also for the uncoated laser diodes with increasing threshold the differential gain is decreasing. This is consistent with an increase in absorption at the laser facet. Degradation is observed during operation but not during storage at ambient conditions and thus expected to be photon or current induced. Judging from ongoing aging studies we tend to exclude two possible mechanisms of facet degradation. (a) Recombination enhanced defect generation. For this mechanism degradation would increase with photon density. We compare aging measurements at a constant current which is above threshold for the laser diodes with mirror coatings and below threshold for the uncoated laser diodes. Because the degradation is slower for lasers with mirrors which are lasing during aging and thus have a higher photon density we can exclude this degradation mechanism. (b) Short circuit via a current path including the laser facet. As we did observe no change in I-V characteristics during aging this mechanism is also an unlikely cause of aging.

11:45 AM Y11.11
Low-Resistance, High Yield Ohmic-Contact to GaN-Based HEMTs. Karim S. Boutros[1], B Brar[1], M Regan[1], D Buttari[2] and U Mishra[2]; [1]Materials and Devices, Rockwell Scientific Company, Thousand Oaks, California; [2]University of California Santa Barbara, Santa Barbara, California.

Low resistance ohmic contacts are key to high performance GaN HEMTs for microwave and mm-wave applications. State-of-the-art Ti-based contacts, which are widely used in GaN HEMT processes, have Rc < 0.5 ohm-mm, and have resulted in record device performance. However, these contacts suffer from poor edge definition and surface roughness due to non-uniform alloy formation during contact anneal. This results in a compromise of performance at the expense of device yield, since the contact roughness forces the placement of the gate far from the source. A low-resistance Ta-based ohmic contact with improved characteristics is reported. The contact has a smooth surface and a high edge-acuity after alloying. This feature leads to a high device yield (> 85%) over a 2-inch wafer, for devices with gate-to-source spacing of 0.45 micron. An alloying process window, which is largely insensitive to both temperature and time, exists for this contact scheme making it favorable from the viewpoint of reproducibility. However, the contact resistance is found to be very sensitive to the surface condition prior to metal deposition. A short oxide-etch in an ICP dry-etch tool, prior to deposition of the ohmic metal, resulted in a reproducible high quality ohmic contact. Our process results in average Rc value of < 0.5 ohm-mm over multiple lots of 2-inch wafers from different vendors. Additionally, breakdown voltages in excess of 100 V have been obtained on devices with 0.3 micron long gates as a result of the sharp contact definition. An Ft/Fmax of 80/120 GHz, and a Gm of 300 mS/mm have also been measured on the same devices, making the Ta-based ohmic contact suitable for implementation in RF device. We will report on the results and experimental conditions studied to develop this ohmic contact scheme. We will also present wafer-level device parameter uniformity data using this contact scheme.

SESSION Y12: InN/Mixed Nitrides
Chair: Hock Min Ng
Friday Afternoon, December 5, 2003
Room 312 (Hynes)

1:30 PM *Y12.1
Band-Gap Energy and Physical Properties of InN Grown by RF-Molecular Beam Epitaxy. Yasushi Nanishi[1], Yoshiki Saito[1], Tomohiro Yamaguchi[1], Fumie Matsuda[1], Tsutomu Araki[1], Akira Suzuki[2], Hiroshi Harima[3] and Takao Miyajima[4]; [1]Department of Photonics, Ritsumeikan University, Kusatsu, Japan; [2]Research Organization of Science and Engineering, Ritsumeikan University, Kusatsu, Japan; [3]Department of Electronics and Information Science, Kyoto Institute of Technology, Kyoto, Japan; [4]Core Technology Development Center, Core Technology & Network Company,Sony Corporation, Atsugi, Japan.

Band-gap energy of InN has long been believed to be 1.9 eV after it has been reported from optical absorption experiments using poly-crystalline InN and InGaN. Recent studies on MOCVD and RF-MBE growth of InN enabled us to obtain high-quality single crystalline InN and good electrical properties such as room temperature electron mobility over 2100 cm^2/Vs and residual carrier concentration close to $3x10^{17}/cm^3$ were reported [1]. Very recent studies on PL, optical absorption and photo-reflectance measurements using high-quality InN have demonstrated that the fundamental band-gap of single crystalline InN should be 0.7-0.8 eV [2,3]. In this presentation, we review recent studies on high-quality InN and InGaN growth by RF-MBE on sapphire. To obtain high-quality InN, the following growth conditions were found to be essential; which were (1) nitridation of the sapphire substrate, (2) two-step growth, (3) precise control of V/III ratio and (4) selection of optimum growth temperature. Characterization studies using XRD, TEM, EXAFS and Raman scattering have clearly demonstrated that InN grown in this

study have ideal hexagonal wurtzite structure. The full widths at half maximum (FWHMs) of ω mode XRD, ω-2θ mode XRD and E_2 (high) mode peak in the Raman scattering spectrum of the grown layer were as small as 236.7 arcsec, 28.9 arcsec and 3.2 cm^{-1}, respectively. The carrier concentration and room temperature mobility were $4.9x10^{18}cm^{-3}$ and 1130 cm^2/Vs. InGaN films with full compositional range were also successfully grown on sapphire substrates. PL and CL studies both on these well-characterized high-quality InN and full composition InGaN films have clearly demonstrated that band-gap energy of InN should be less than 0.75 eV, approximately 0.7 eV at room temperature. For determination of accurate band-gap energy of InN, however, further reduction in residual carrier concentration should be needed. Possible application fields of narrow band-gap InN and issues for further application to devices will be discussed. Our latest studies on polarity of InN and InN growth on Si substrates should also be included in this presentation. [1] H. Lu et al; MRS Symposium Proceedings 743, *I4*.10 (2003). [2] V. Y. Davydov et al; phys. stat. sol. (b) 229, R1 (2002). [3] J. Wu et al; Appl. Phys. Lett. 80, 3967 (2002). This work was supported by MEXT, Grant-in-Aid for Scientific Research (B)#13450131, Academic Frontier Project and the 21st Century COE Program.

2:00 PM Y12.2
Epitaxilal Growth of High Quality InN Films With PLD.
Hiroshi Fujioka[1,2], Takashi Honke[1], Jitsuo Ohta[1] and Masaharu Oshima[1]; [1]Department of Applied Chemistry, The University of Tokyo, Bunkyo-ku, Tokyo, Japan; [2]Kanagawa Academy of Science and Technology, Kawasaki, Kanagawa, Japan.

We have grown InN films on sapphire (0001) and YSZ (111) by pulsed laser deposition (PLD) for the first time and investigated the effect of the substrate on the structural properties of the InN films with RHEED, HRXRD, XTEM, and AFM. Growths of InN are performed in a PLD apparatus with a background pressure of $1.0x10^{-10}$ Torr. RHEED patterns for InN on both sapphire and YSZ are sharp streaks, which indicates that high quality InN grows with flat surfaces. Careful interpretation of RHEED patterns led us to conclude that InN (0001) grows on both substrates and the in-plane epitaxial relationships for sapphire and YSZ are InN [10-10] // sapphire [11-20] and InN [11-20] // YSZ [1-10], respectively. The lattice mismatches estimated from these in-plane alignments for sapphire and YSZ are 29 % and 2.3%, respectively. Drastic reduction in the lattice mismatch by the use of YSZ substrates improved structural properties of the InN films. Altough it is well known that the reduction in the twist angle of InN is quite difficult, the FWHM values of the 20-24 X-ray rocking curves for InN grown on sapphire and YSZ are 34.8 arcmin and 20.8 arcmin, respectively. XTEM observations revealed that the threading dislocation density for the InN grown on YSZ is quite low (10^9 cm^{-2}). These results indicate that the use of PLD and YSZ (111) substrates is promising for the epitaxial growth of high quality InN films.

2:15 PM Y12.3
Optical and Microstructural Characteristics of InN on (0001) Sapphire and (001) YSZ by Plasma-Assisted Molecular Beam Epitaxy.
P A Andersón[1], C E Kendrick[1], T E Lee[1], W Diehl[2], R J Reeves[2], V J Kennedy[3], A Markwitz[3], R J Kinsey[1] and S M Durbin[1]; [1]Electrical & Computer Engineering, University of Canterbury, Christchurch, New Zealand; [2]Department of Physics, University of Canterbury, Christchurch, New Zealand; [3]Institute of Geological & Nuclear Sciences, Ltd., Lower Hutt, New Zealand.

Determination of the optical properties of InN is relevant for understanding the detailed behaviour of InGaN alloys. Recent reports that the bandgap energy may be much lower than the commonly quoted value of 1.89 eV—possibly as low as 0.6 eV—has led to renewed interest, however, as this would enable a new range of applications for the material, such as high-efficiency multi-junction photovoltaic devices. If true, it would also impact interpretation of indium-rich regions (such as self-assembling quantum dot like structures) within InGaN layers. We have investigated the optical and structural properties of InN grown on both (0001) sapphire and cubic (001) YSZ substrates using a plasma-assisted molecular beam epitaxy (PAMBE) technique. Film thickness is typically on the order of 300 nm, corresponding to a growth rate of 100 nm/ hr. Single crystal films are obtained for substrate temperatures in the range of 350-550°C, as confirmed by in-situ reflection high-energy electron diffraction (RHEED). The only photoluminescence features are observed between 0.7 and 0.8 eV, and have linewidths of approximately 60 to 150 meV, depending on growth conditions. Despite intensive searching, no luminescence features in the visible region can be observed above the limits determined by laser scatter. As the temperature of the sample is increased, the peak often exhibits a blue shift of several meV as noted by other groups, and reduces in intensity until becoming too weak to detect above 150 K. The opposite behaviour is observed for a film grown on (001) YSZ however, where a distinct red shift is observed with increasing temperature, as would be expected from a bandedge-related feature. An increase in intensity with increasing temperature is also observed in the same sample. For films grown on sapphire, two distinct regimes are observed. The first regime is characterised by spotty RHEED patterns, and a surface morphology consisting of very flat interconnected plateaus exhibiting distinct hexagonal symmetry. The hexagonal features, having a size of approximately 100 nm, are well aligned across the film. The second regime is obtained for increased N_2:In ratios, where streaky RHEED features are observed. AFM analysis of the surface shows distinct isolated columnar features with hexagonal symmetry and a width of approximately 1 micron. Interestingly, photoluminescence is observed from these films as well. Rutherford backscattering spectroscopy shows the presence of a thin (~40 nm) layer of indium oxynitride at the surface of all films, with an essentially stoichiometric and oxygen-free (to within measurement resolution) InN layer beneath. Nucleation of InN on YSZ is initially cubic, but the film quality rapidly deteriorates. AFM of the final film surface is suggestive of features having cubic rather than hexagonal symmetry, although the roughness is comparable to the film thickness. Luminescence from these films is comparable to that of films grown on sapphire.

2:30 PM Y12.4
Microstructure of InN Films Grown on GaN by Metal-Organic Vapor Phase Epitaxy.
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The band-gap of InN was thought to be 1.9eV, but recent results have shown that it may be a much lower value. Little work has been done to understand the microstructural properties of InN, and their effect on the optoelectronic properties. In this work, we have studied a set of InN samples grown under different conditions, using XRD and TEM. Two InN films were deposited on GaN templates using metal-organic vapor phase epitaxy at 500 and 450 degree Celsius. The first sample has a background carrier concentration of 5.8x10E18 cm-3 and an absorption edge of ~0.8eV, while the values for the latter are 7.6x10E19 cm-3 and ~1.1eV. XRD analysis indicates that the c lattice parameter of the sample grown at 500 degree Celsius is larger (5.701 vs. 5.662 angstroms), and closer to the tabulated value from InN powder diffraction. TEM images show significant difference between the microstructure of two samples. The sample grown at high temperature produces better crystalline quality material, with mostly one-dimensional threading dislocations. The lower temperature growth is dominated by two-dimensional grain boundaries. Lattice images show a well-defined InN/GaN interface for both samples. It is evident that the lattice mismatch strain is relaxed. InN lattice constants on the basal plane are estimated from lattice images to be 3.55 and 3.53 angstroms for growth at 500 and 450 degree Celsius respectively. We find that the improved crystalline quality InN grown at higher temperature is associated with a larger unit cell, and a lower background carrier density. With this work, we have shown that the crystalline quality of the material strongly affects the optoelectronic properties, so it is important that microstructure is considered when determining the band-gap of InN.

2:45 PM Y12.5
Temperature Dependence of the Optical Properties for InN Films Grown By RF-MBE.
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Recently the bandgap energy Eg of InN was proved to be less than 1 eV. Many researchers have started the study on InN for the sake of application to ultra-fast optical communication devices. However several basic physical parameters are not yet determined. Although a few values of the effective electron mass (me*) were reported, there is no data obtained by optical reflectance analysis taking account of the TO phonon and LO phonon-plasma-coupling mode frequencies in a wide wavenumber range as 350-8000 cm-1, also using thick films (several micrometers). Eg for the intrinsic crystal was reported as 0.68eV.1) Temperature dependence of the PL peak energy was reported to decrease with decrease in temperature in contrast to novel semiconductors.2) However there is no report on the dependence of the transmission spectrum. We measured the optical reflectance and transmission spectra in a range of 5 - 300 K for samples with thickness of 1-7.5 μm and carrier concentration Ne of 1.5 -11E18 cm-3. We estimated me* of the intrinsic crystal as 0.097 (-0.004), and also determined the parameters for non-parabolic conduction band. Since the plasma edge is constant with the temperature decrease, a band of impurity or defect is formed. Thus the estimated Eg from absorption edge is probably smaller than the actual one. The absorption edge energy increases with the decrease in temperature to 50 K, below which it decreases. From 50 to 5 K the decrease in the

edge energy is smaller for smaller Ne: 3 meV for 4E18 cm-3. The temperature dependence of Eg for intrinsic crystal is estimated to have the similar one to novel III-V semiconductors. The decrease of Eg with the decrease from 300 to 50 K was estimated to be 25 - 40 meV. 1) J.Wu, W.Walukiewicz, W.Shan, K.M.Yu, J.W.Ager, E.E.Haller, H.Lu, and W.J.Schaff, Phys. Rev. B, 66, 2-1403 (2002). 2) J.Wu, W.Walukiewicz, K.M.Yu, J.W Ager, E.E.Haller, H.Lu, W.J.Schaff, Y.Saito, and Y.Nanishi, Appl. Phy. Lett. 80, 3967 (2002)

3:30 PM Y12.6

Growth of Non-polar a-plane and Cubic InN on r-plane Sapphire by Molecular Beam Epitaxy. Hai Lu[1], William J Schaff[1], Lester F Eastman[1], Volker Cimalla[2], Oliver Ambacher[2], J. Wu[3] and W. Walukiewicz[3]; [1]Electrical and Computer Engineering, Cornell University, Ithaca, New York; [2]Center for Micro- and Nanotechnologies, Technical University Ilmenau, Ilmenau, Germany; [3]Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California.

Growth of non-polar III-nitrides has been an important subject recently due to its potential improvement on the efficiency of III-nitride-based opto-electronic devices. Despite of the intensively studied non-polar GaN and GaN-based heterostructures, there are very few reports on epitaxial growth of non-polar InN, which is also an important component of the III-nitride system. Moreover, recently this material has received much attention due to the discovery of its narrow band gap around 0.7 eV. This discovery greatly extends the range of emission spectrum of III-nitrides, and thus makes it possible to fabricate III-nitride-based light emitter over a broader wavelength range from infrared to ultraviolet. In this study, we first report heteroepitaxial growth of non-polar InN on r-plane sapphire substrates using plasma-assisted molecular beam epitaxy. It is found that when a GaN buffer is used, the following InN film appears to be non-polar (11$\bar{2}$0) a-plane which follows the a-plane GaN buffer. Optical absorption and photoluminescence measurements of this material show that InN has a fundamental bandgap of about 0.7 eV which is also seen for growth on c-plane sapphire. The room temperature Hall mobility of undoped a-plane InN is around 250 cm^2/Vs with a carrier concentration around 6×10^{18} cm^{-3}. Meanwhile, if InN film is directly deposited on r-plane sapphire without any buffer, the InN layer is found to consist of a predominant zincblende (cubic) structure along with a fraction of the wurtzite (hexagonal) phase which content increases with proceeding growth. A model is purposed to explain this unusual epitaxial relationship in which a metastable cubic phase forms on a noncubic substrate while the wurtzite phase arises as the special case of twinning in the cubic structure.

3:45 PM Y12.7

Optical and Electrical Properties of Non-Degenerate and Highly Degenerate InN Films. Daad B. Haddad[1], Jagdish S Thakur[2], Vaman M Naik[3], Gregory W Auner[2], Ratna Naik[1], Lowell E Wenger[1], Hai Lu[4] and William J Schaff[4]; [1]Department of Physics and Astronomy, Wayne State University, Detroit, Michigan; [2]Department of Electrical and Computer Engineering, Wayne State University, Detroit, Michigan; [3]Department of Natural Sciences, University of Michigan-Dearborn, Dearborn, Michigan; [4]Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York.

The influence of electron carrier concentration (not intentionally doped), n, on the optical and electrical properties of two different InN films has been investigated. Sample A is an InN film, 2 μm thick grown on a GaN buffer layer on (0001) sapphire substrate by molecular beam epitaxy, with $n \sim 7.5 \times 10^{17}$ cm^{-3} and a mobility of $\sim$ 1488 cm^2/Vs as measured by Hall effect at room temperature. Sample B is an InN film, 0.5 μm thick grown by plasma source molecular beam epitaxy on (0001) sapphire, with $n \sim 3 \times 10^{20}$ cm^{-3} and a mobility of $\sim$ 55 cm^2/Vs. Superior crystalline quality of the former film was confirmed by both x-ray diffraction and Raman scattering. Analyses of optical absorption spectra of both films, determined using transmission and reflection data, show an optical bandgap absorption $\sim$ 0.6 eV for sample A and 1.5 eV for sample B. The latter sample also shows a plasmon absorption peak around 0.5 eV due to a very high carrier concentration. It has been recently shown that the observed high values for the InN bandgap is due to a Moss-Burnstein shift in highly degenerate InN films. Temperature dependent (5 - 350 K) measurements of the extrinsic electrical resistivity clearly show a semiconducting behavior for sample A with an activation energy of $\sim$ 2 meV. On the other hand, a metallic type of conductivity was observed with a residual resistivity ratio of 1.07 for sample B. Results from higher temperature (> 350 K) resistivity measurements will also be presented to check the intrinsic band gap behavior.

4:00 PM Y12.8

Study of the Growth Mechanism and Properties of InN Films Grown by MOCVD. Abhishek Jain[1], Joan M Redwing[1], Lynn Gedvilas[2] and Brian Keyes[2]; [1]Materials Science and Engineering, Materials Research Institute, Pennsylvania State University, University Park, Pennsylvania; [2]National Renewable Energy Laboratory, Golden, Colorado.

InN is an important group III-nitride semiconductor because of its unique electrical and optical properties. Theoretically, it has a low effective mass of electrons, which makes it suitable for high speed devices. Recent studies indicate that the bandgap energy of InN lies in the infrared, which has stimulated interest in solar cell applications. The barrier to successful fabrication of InN based devices is the limited success in growing films with low surface roughness, good crystal quality and low unintentional n-type doping. We have investigated the MOCVD growth of InN on sapphire substrates, using in-situ laser reflectance to study the evolution of surface roughness during layer growth. InN films were deposited at a growth temperature of 560°C and a reactor pressure of 650 Torr using trimethyl indium mole fractions in the range of 2×10^{-5}-6×10^{-5}, V (NH_3)/III ratios of 10^4-3×10^4 and nitrogen as the carrier gas. AlN buffer layers, deposited at 500°C, were used for growth of InN on sapphire and films were also deposited on 2 μm thick MOCVD-grown GaN layers on sapphire. After an increase in the reflected laser intensity during the initial segment of growth due to the deposition of InN on sapphire, the laser intensity decreased significantly, which correlated to a change in the growth mode of the film from 2D to 3D and increased surface roughness. A room temperature mobility of 1268 cm^2/V-s was measured in a 330 nm thick InN layer grown on GaN that had a background electron concentration of 6.7×10^{18} cm^{-3}. The ωscan FWHM of the (0002) reflection of InN was 830 arcsec for this layer. Preliminary photoluminescence measurements carried out on the MOCVD InN films reveal an emission peak at $\sim$0.71 eV, consistent with results recently reported for MBE-grown material.

4:15 PM Y12.9

Hydrostatic Pressure Dependence of the Fundamental Bandgap of InN and In-Rich InGaN and InAlN Alloys. Sonny X. Li[1,2], Junqiao Wu[1,2], Wladyslaw Walukiewicz[2], Wei Shan[2], Eugene E. Haller[1,2], Hai Lu[3] and William J. Schaff[3]; [1]Department of Materials Science and Engineering, University of California, Berkeley, Berkeley, California; [2]Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California; [3]Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York.

The recent discovery of the fundamental bandgap of InN near 0.7 eV has attracted renewed attention to the properties of InN and In-rich nitride alloys. We have studied the hydrostatic pressure dependence of the fundamental bandgap of InN, In-rich $In_{1-x}Ga_xN$ ($0 < x < 0.5$) and $In_{1-x}Al_xN$ (x =0.25) alloys. The shifts of the bandgaps were measured by optical absorption experiments in diamond anvil cells. The pressure coefficient was determined to be 3.0 $\pm$ 0.1 meV/kbar for InN. The values of the pressure coefficients of the In-rich alloys are very close to that of InN. These results agree reasonably well with theoretical predictions. Together with previous experimental results (pressure coefficient $\sim$4 meV/kbar for GaN [1] and $\sim$5 meV/kbar for AlN [2]), our data indicate that the pressure coefficient of group-III nitrides has only a weak dependence on the alloy composition. The small pressure coefficient of group-III nitrides as compared to other III-V compounds can be attributed to their high ionicity, which also explains the decrease of the pressure coefficient with increasing cation atomic number of the nitrides. We also found that the pressure coefficient of the photoluminescence peak energy of InN amounts to only 0.6 to 0.9 meV/kbar and is much smaller than the pressure coefficient of the absorption edge energy. This result suggests that highly localized levels could be involved in the radiative recombination process. [1] W. Shan, W. Walukiewicz, E. E. Haller, B. D. Little, J. J. Song, M. D. McCluskey, N. M. Johnson, Z. C. Feng, M. Schurman, and R. A. Stall, J. Appl. Phys. **84**, 4452 (1998). [2] Hisamitsu Akamaru, Akifumi Onodera, Tadashi Endo, Osamu Mishima, J. Phys. Chem. Solids **63**, 887 (2002). Supported by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

4:30 PM Y12.10

N-rich GaNAs with High As Content Grown by Metalorganic Vapor Phase Epitaxy. Akitaka Kimura[1], H. F. Tang[1], C. A. Paulson[2] and T. F. Kuech[1]; [1]Department of Chemical and Biological Engineering, University of Wisconsin-Madison, Madison, Wisconsin; [2]Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, Wisconsin.

N-rich GaNAs is an attractive material for extending the wavelength range of GaN-based blue-light-emitting devices toward the red/infrared region, since it has a narrower bandgap at smaller strain than InGaN alloy. GaAs-based long wavelength devices could be replaced with GaN-based devices reducing the use of As-based substrates and materials while allowing multi-wavelength light emitting devices to be integrated on a single substrate. GaNAs has a very large bandgap bowing parameter attributed to a large difference in the atomic radius between N and As. This alloy system does,

however, possess a large miscibility gap which has limited the achieved As content within the GaN1-yAsy system to only $y \leq 0.03$. An As content of $y \geq 0.07$ is considered necessary for 650 nm emission. We report the growth and properties of N-rich GaN1-yAsy alloy with As content over the range of $y \leq 0.064$. GaNAs layers were grown to a thickness of 0.25 μm on GaN layers on sapphire substrates by low-pressure (76 Torr) metalorganic vapor phase epitaxy. The sources were trimethyl gallium, ammonia, and tertiarybutyl arsine. The carrier gas was hydrogen and the growth temperature was 700-750°C. The epitaxial layers were characterized by X-ray diffraction (XRD) and atomic force microscopy (AFM). Electron probe microanalysis (EPMA) was used to determine As content in the films. The electronic structure was monitored by optical absorption and reflectivity measurements. The GaNAs layers possessed a yellow hue and had specular surfaces. AFM measurements determined a typical root mean square surface roughness of 0.7 nm for a 10-nm-thick GaN0.98As0.02 layer. Each sample had two diffraction peaks: one from the underlying GaN and the other attributed to the GaNAs layer on the low-angle side of the GaN peak in its XRD rocking curve. No peaks that were related to As-rich GaNAs phases were observed in the wide range of XRD $\theta/2\theta$ spectra. The As incorporation into the GaNAs layers increased through both a decrease in the growth temperature as well as a decrease in V/III ratio from 13000 to 1400. These observed trends are similar to that found in other III-V alloy systems, such as GaAsSb. At high V/III ratios, thermodynamic constraints restrict the incorporated As to a low value. Low V/III ratios favor a kinetically limited competition and incorporation of the anion species. Through the use of growth conditions which enhance these kinetic processes, alloy compositions within the miscibility gap were achieved. The highest achieved value of As content of 6.4% was obtained by both decreasing the growth temperature and the V/III ratio. To our knowledge, this is the highest As content of N-rich GaNAs alloy that has been reported to date. The results of the optical measurements in regard to determining the optical band gap of the material will be discussed.

4:45 PM Y12.11
Abstract Withdrawn